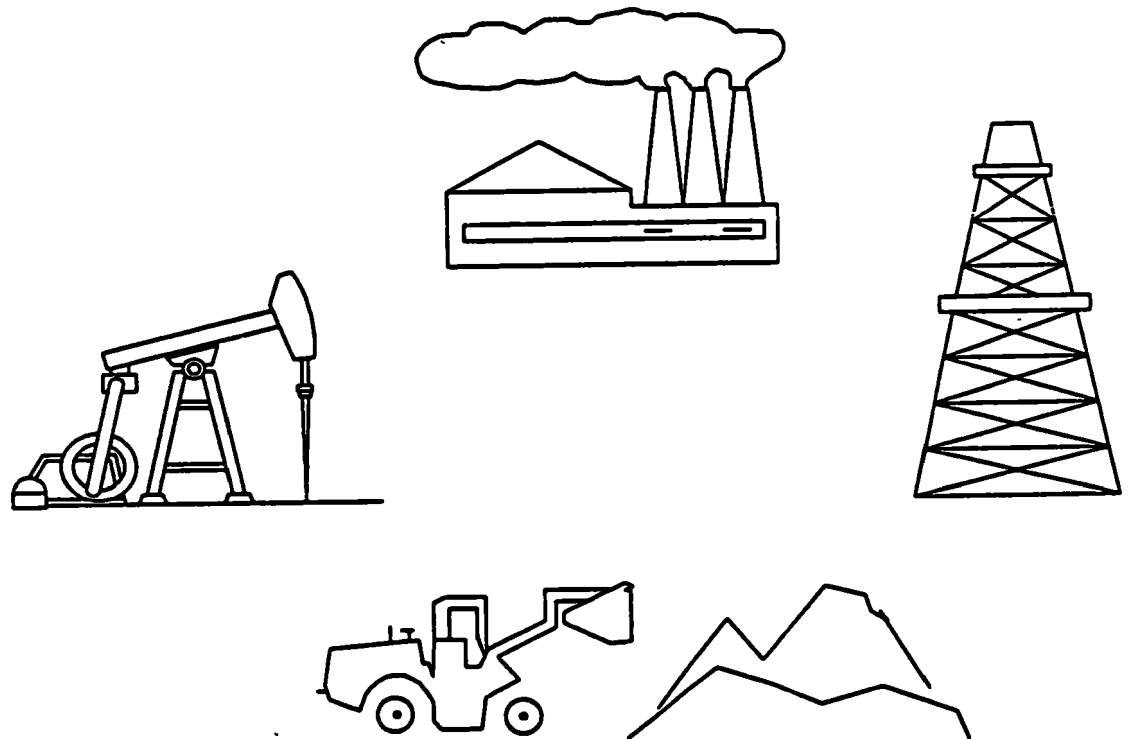




Diffuse Norm

Draft

Waste Characterization And Preliminary Risk Assessment



- DRAFT -

**- DIFFUSE NORM WASTES -
WASTE CHARACTERIZATION AND RISK ASSESSMENT**

Prepared By

**SC&A, Inc.
1311 Dolley Madison Boulevard
McLean, Virginia 22101
(703) 893-6592**

and

**Rogers & Associates Engineering Corp.
P.O. Box 330
Salt Lake City, Utah 84110-0330**

and

**Roy F. Weston, Inc.
5301 Central Ave., N.E.
Albuquerque, New Mexico 87108**

**Contract No. 68-D90170
Work Assignment 1-59**

Prepared For

**U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Radiation Programs
401 M Street, S.W.
Washington, D.C. 20460**

**William E. Russo/James M. Gruhlke
Work Assignment Manager**

May 1991

TABLE OF CONTENTS

<u>Chapter</u>	<u>Page No.</u>
EXECUTIVE SUMMARY	ES-1
A. INTRODUCTION	A-1
B.1 URANIUM MINING OVERBURDEN	B-1-1
1.1 Introduction	B-1-1
1.2 Overview of the Uranium Mining Industry	B-1-2
1.2.1 Surface Mining	B-1-2
1.2.2 Underground Mining	B-1-6
1.2.3 Other Mining Methods	B-1-7
1.3 Ore and Waste Production	B-1-7
1.3.1 Waste Volume Projections	B-1-8
1.3.2 Reclaimed Versus Unreclaimed Material	B-1-12
1.3.3 Uranium Overburden Utilization	B-1-13
1.3.4 Twenty-Year Projection of Unreclaimed Waste	B-1-16
1.4 Radiological Properties of Uranium Mine Waste	B-1-19
1.4.1 Radionuclide Concentrations	B-1-19
1.4.2 Radon Flux Rates	B-1-20
1.4.3 External Radiation Exposure Rates	B-1-21
1.5 Generic Site Parameters and Sector Summary	B-1-22
1.5.1 Generic Overburden Site	B-1-22
1.5.2 Population Exposure	B-1-22
1.5.3 Radionuclide Concentrations	B-1-23
B.1 References	B-1-R-1
B.2 PHOSPHATE AND ELEMENTAL PHOSPHOROUS WASTES	B-2-1
2.1 Introduction	B-2-1
2.2 Overview of Phosphate Industry	B-2-2
2.2.1 Phosphoric Acid - Wet-Process	B-2-5
2.2.2 Elemental Phosphorous - Thermal Process	B-2-8
2.3 Phosphogypsum Stacks and Elemental Phosphorous Wastes	B-2-11
2.3.1 Volume of Waste Materials	B-2-11
2.3.2 Phosphogypsum and Slag Utilization	B-2-14
2.3.3 Twenty-Year Waste Inventory	B-2-17
2.4 Radiological Properties of Phosphogypsum and Slag	B-2-20
2.4.1 Radionuclide Concentrations of Phosphogypsum and Slag	B-2-20
2.4.2 Radon Flux Rates	B-2-23
2.4.3 External Exposure Rates	B-2-25
2.5 Generic Site Parameters and Sector Summary	B-2-28
2.5.1 Generic Phosphogypsum Stack	B-2-28

TABLE OF CONTENTS

(Continued)

<u>Chapter</u>		<u>Page No.</u>
(B.2)	2.5.2 Population Exposure	B-2-29
	2.5.3 Radionuclide Concentrations	B-2-29
B.2	References	B-2-R-1
 B.3	 PHOSPHATE FERTILIZERS	 B-3-1
	3.1 Introduction	B-3-1
	3.2 Production of Phosphate Fertilizers	B-3-2
	3.2.1 Phosphoric Acid Production	B-3-2
	3.2.2 Phosphate Fertilizer Production	B-3-3
	3.3 Phosphate Fertilizer Consumption	B-3-3
	3.3.1 Consumption and Application Rates	B-3-3
	3.3.2 Twenty-Year Fertilizer Production Estimates	B-3-7
	3.4 Radiological Properties of Fertilizers	B-3-8
	3.4.1 Radionuclide Concentrations	B-3-8
	3.4.2 Radon Flux Rates	B-3-12
	3.4.3 Radiation Exposure Rates	B-3-12
	3.5 Generic Site Parameters and Sector Summary	B-3-14
	3.5.1 Generic Agricultural Site	B-3-14
	3.5.2 Population Exposure	B-3-14
	3.5.3 Radionuclide Concentrations	B-3-14
B.3	References	B-3-R-1
 B.4	 FOSSIL FUELS - COAL ASH	 B-4-1
	4.1 Introduction	B-4-1
	4.2 Overview of Coal Ash Generation	B-4-2
	4.2.1 Coal-Fired, Steam-Electric Generating Stations	B-4-2
	4.2.2 Industrial Boilers	B-4-3
	4.3 Coal Ash Generation	B-4-3
	4.3.1 Production of Coal Ash	B-4-3
	4.3.2 Coal Ash Disposal	B-4-8
	4.3.3 Coal Ash Utilization	B-4-10
	4.3.4 Twenty-year Coal Ash Inventory Estimate	B-4-14
	4.4 Radiological Properties of Coal Ash	B-4-17
	4.4.1 Radionuclide Concentrations	B-4-17
	4.4.2 Radon Flux Rates	B-4-19
	4.4.3 External Radiation Exposure Rates	B-4-21
	4.5 Coal Ash NORM Sector Summary	B-4-23
	4.5.1 Generic Coal Ash Disposal Site	B-4-23
	4.5.2 Population Exposure	B-4-24
	4.5.3 Radionuclide Concentrations	B-4-24
B.4	References	B-4-R-1

TABLE OF CONTENTS

(Continued)

<u>Chapter</u>		<u>Page No.</u>
B.5	OIL AND GAS PRODUCTION SCALE	B-5-1
5.1	Introduction	B-5-1
5.2	Overview of Oil and Gas Production	B-5-4
5.3	Oil and Gas Scale and Sludge Waste Production	B-5-11
5.3.1	Origin and Nature of NORM in Oil and Gas Scale and Sludge	B-5-11
5.3.2	Oil and Gas Scale and Sludge Production Rates	B-5-15
5.3.3	Oil and Gas Scale Handling and Disposal	B-5-18
5.3.4	Twenty-Year Oil and Gas Scale and Sludge Volume Estimates	B-5-20
5.4	Radiological Properties of Oil and Gas Scale and Sludge	B-5-21
5.4.1	Radionuclide Concentrations	B-5-21
5.4.2	Radon Flux Rates	B-5-24
5.4.3	External Radiation Exposures Rates	B-5-24
5.5	Summary of Oil and Gas NORM Sector	B-5-30
5.5.1	Generic Oil and Gas Scale Disposal Site	B-5-30
5.5.2	Population Exposure	B-5-30
5.5.3	Radionuclide Concentrations	B-5-30
B.5	References	B-5-R-1
 B.6	 WATER TREATMENT SLUDGES	 B-6-1
6.1	Introduction	B-6-1
6.2	Overview of Water Supply Systems	B-6-2
6.2.1	Areas of Elevated Water Radionuclide Concentrations	B-6-2
6.2.2	Water Treatment Technology	B-6-5
6.3	Water Treatment Waste Generation	B-6-8
6.3.1	Water Treatment Waste Generation	B-6-8
6.3.2	Water Treatment Waste Disposal Methods	B-6-12
6.3.3	Utilization of Water Treatment Wastes	B-6-15
6.3.4	Twenty-Year Sludge Generation Estimates	B-6-19
6.4	Radiological Properties of Treatment Sludge	B-6-20
6.4.1	Radionuclide Concentrations	B-6-20
6.4.2	Radon Flux Rates	B-6-23
6.4.3	External Radiation Exposure Rates	B-6-23
6.5	Generic Site Parameters and Sector Summary	B-6-24
6.5.1	Generic Water Treatment Site	B-6-24
6.5.2	Population Exposure	B-6-25
6.5.3	Radionuclide Concentrations	B-6-26
B.6	References	B-6-R-1

TABLE OF CONTENTS

(Continued)

<u>Chapter</u>		<u>Page No.</u>
B.7	METAL MINING AND PROCESSING WASTE	B-7-1
7.1	Introduction	B-7-1
7.2	Overview of the Metal Mining Industry	B-7-3
7.2.1	Metal Mining and Waste Production	B-7-3
7.2.2	Bauxite and Aluminum	B-7-5
7.2.3	Copper	B-7-8
7.2.4	Zinc	B-7-19
7.2.5	Tin	B-7-21
7.2.6	Titanium	B-7-22
7.2.7	Zirconium and Hafnium	B-7-24
7.2.8	Ferrous Metals (Iron and Carbon Steel)	B-7-26
7.2.9	Lead	B-7-33
7.3	Mineral Processing Waste Generation	B-7-36
7.3.1	Mineral Processing Waste Production	B-7-36
7.3.2	Utilization and Disposal of Bulk Waste Materials	B-7-39
7.3.3	Twenty-Year Waste Generation Estimates	B-7-41
7.4	Radiological Properties of Mineral Processing Wastes	B-7-43
7.4.1	Radionuclide Concentrations	B-7-43
7.4.2	Radon Flux Rates	B-7-44
7.4.3	External Radiation Exposure Rates	B-7-44
7.5	Generic Site Parameters and Sector Summary	B-7-46
7.5.1	Generic Mineral Processing Waste Site	B-7-46
7.5.2	Population Distribution	B-7-47
7.5.3	Radionuclide Concentrations	B-7-47
B.7	References	B-7-R-1
B.8	GEOHERMAL ENERGY PRODUCTION WASTE	B-8-1
8.1	Introduction	B-8-1
8.2	Overview of the Geothermal Energy Industry	B-8-3
8.2.1	Electrical Power Production	B-8-5
8.2.2	Direct Use of Geothermal Energy	B-8-9
8.3	Geothermal Energy Waste	B-8-12
8.3.1	Exploration and Development Wastes	B-8-13
8.3.2	Geothermal Power Plant Wastes	B-8-13
8.3.3	Waste Generation from Direct Users	B-8-14
8.3.4	Twenty-Year Waste Generation Estimate	B-8-15
8.4	Radiological Properties of Geothermal Energy Wastes	B-8-15
8.4.1	Radionuclide Concentrations	B-8-15
8.4.2	Radon Flux from Geothermal Wastes	B-8-17
8.4.3	External Radiation Exposure Rates	B-8-17
8.5	Summary of Geothermal Energy NORM Sector	B-8-18
8.5.1	Generic Geothermal Solid Waste Disposal Site	B-8-18

TABLE OF CONTENTS

(Continued)

<u>Chapter</u>		<u>Page No.</u>
(B.5)	8.5.2 Population Exposure	B-8-18
	8.5.3 Radionuclide Concentrations	B-8-19
B.8	References	B-8-R-1
 D.1	 RISK ASSESSMENT FOR DIFFUSE NORM	 D-1-1
	D.1 Introduction	D-1-1
 D.2	 RISK ASSESSMENT METHODS	 D-2-1
	2.1 The PATHRAE Dose Assessment Model	D-2-1
	2.2 Exposure Scenarios	D-2-2
	2.2.1 Worker -- Direct Gamma Exposure	D-2-2
	2.2.2 Worker -- Dust Inhalation	D-2-3
	2.2.3 Worker -- Indoor Radon Inhalation	D-2-4
	2.2.4 Onsite Individual	D-2-4
	2.2.5 Onsite Individual -- Indoor Radon Inhalation	D-2-5
	2.2.6 Member of CPG -- Direct Gamma Exposure	D-2-5
	2.2.7 Member of CPG -- Inhalation of Contaminated Dust	D-2-6
	2.2.8 Member CPG -- Downwind Exposure to Radon	D-2-8
	2.2.9 Member of CPG -- Exposure to NORM in Building Materials	D-2-10
	2.2.10 Member of CPG -- Ingestion of Drinking Water from a Contaminated Well	D-2-11
	2.2.11 Member of CPG -- Ingestion of Foodstuffs Contaminated by Well Water	D-2-13
	2.2.12 Member of CPG -- Ingestion of Foodstuffs Contaminated by Dust Deposition	D-2-13
	2.2.13 Member of CPG -- Ingestion of Foodstuffs Grown on Repeatedly Fertilized Soil	D-2-14
	2.2.14 Population -- Downwind Exposure to Resuspended Particulates	D-2-15
	2.2.15 General Population -- Downwind Exposure to Radon	D-2-16
	2.2.16 General Population -- Ingestion of River Water Contaminated via the Groundwater Pathway	D-2-17
	2.2.17 General Population -- Ingestion of River Water Contaminated by Surface Runoff	D-2-18
	2.2.18 General Population -- Ingestion of Foodstuffs Grown on Repeatedly Fertilized Soil	D-2-20
	2.3 Input Parameters	D-2-21

TABLE OF CONTENTS (Continued)

<u>Chapter</u>		<u>Page No.</u>
D.3	RISK ASSESSMENT RESULTS	D-3-1
	3.1 Worker Doses and Risks	D-3-1
	3.2 Doses and Risks to Members of the Critical Population Group (CPG)	D-3-4
	3.3 Population Doses and Risks	D-3-4
	3.4 Benchmarking the Dose Methodology	D-3-7
	3.5 Summary and Conclusions	D-3-7
	References	D-R-1
E.	CONCLUSIONS	E-1-1
	E.1 Conclusions	E-1-1
	E.2 Recommendations	E-1-6
	E.2.1 Waste Volumes and Characteristics	E-1-6
	E.2.2 Radiological Source Term	E-1-8
	E.2.3 Environmental Transport Mechanisms	E-1-9
	E.2.4 Exposure Pathways	E-1-10
	E.2.5 Exposed Populations	F-1-10
	E.2.6 Evaluation of Overall Uncertainties	E-1-11
APPENDIX A:	EXTRAPOLATIONS OF DOSE AND RISK CALCULATIONS TO CHAPTER D	A-1

LIST OF FIGURES

<u>Figure No.</u>		<u>Page No.</u>
A.1-1	Uranium decay chain	A-2
A.1-2	Thorium decay chain	A-3
A.1-3	Actinium series decay chain	A-4
B.2-1	Major uraniferous phosphate deposits in the U.S.	B-2-3
B.2-2	Flow diagram of phosphate material and waste production	B-2-4
B.5-1	Typical production operation, showing separation of oil, gas, and water	B-5-13
B.8-1	Schematic of electric power production from a vapor-dominated system	B-8-6
B.8-2	Schematic of flashed-steam process for producing electric power from a liquid-dominated system	B-8-7
B.8-3	Schematic of binary process for producing electric power from a liquid-dominated system	B-8-8

LIST OF TABLES

<u>Table No.</u>		<u>Page No.</u>
A.1-1	Exposure scenarios for diffuse NORM risk assessment	A-7
B.1-1	Location of surface and underground uranium mine sites in the U.S.	B-1-3
B.1-2	Uranium ore production from 1948 to 1988	B-1-4
B.1-3	Estimated uranium mining overburden production	B-1-9
B.1-4	Surface uranium mining industry based on regional reclamation	B-1-14
B.2-1	Wet process phosphoric acid plants	B-2-6
B.2-2	Location and capacity of elemental phosphorus plants	B-2-9
B.2-3	Location and number of phosphogypsum stacks	B-2-12
B.2-4	Radionuclide concentrations in phosphate ores, phosphogypsum, and slag	B-2-21
B.2-5	Summary of dose and risk results from the Idaho radionuclide exposure study	B-2-27
B.3-1	Trends in phosphate fertilizer demand and application	B-3-5
B.3-2	Phosphate fertilizer consumption 1987-1988	B-3-6
B.4-1	Constituents of coal ash	B-4-5
B.4-2	Actual and projected yearly ash (including fly ash, bottom ash, and boiler slag) production rate	B-4-6
B.4-3	Regional fly ash production and utilization - 1984	B-4-9
B.4-4	Ash and sludge utilization breakdown for 1987	B-4-11
B.4-5	Actual and projected yearly ash utilization rate	B-4-16
B.4-6	Estimated doses and risks from exposures to a coal ash pile	B-4-22

LIST OF TABLES
(Continued)

<u>Table No.</u>		<u>Page No.</u>
B.5-1	U.S. crude oil production	B-5-5
B.5-2	U.S. natural gas production	B-5-6
B.5-3	Crude oil production for 1987 by state	B-5-7
B.5-4	Natural gas production for 1987 by state	B-6-9
B.5-5	Equipment listing and characteristics of a 10-well production facility	B-5-16
B.5-6	Statistical analysis of radiation exposure levels associated with NORM in oil production and gas processing equipment -- national summary	B-5-25
B.5-7	Abbreviations used to designate equipment types in oil production and gas processing facilities	B-5-27
B.6-1	Numbers of public water systems and populations served by sources and size category	B-6-6
B.6-2	Summary of treatment technologies for removal of naturally-occurring radionuclides from water	B-6-7
B.6-3	Distribution of water treatment systems reported in use by 211 water utilities surveyed in 1985	B-6-9
B.6-4	Summary of water utilities operating characteristics for 1984 and 1985	B-6-11
B.6-5	Sludge disposal practices and quantities for 183 utilities in 29 selected states	B-6-13
B.7-1	Bauxite refineries	B-7-6
B.7-2	Radionuclide concentrations in alumina plant process samples	B-7-9
B.7-3	Bauxite open-pit radon surface flux rates	B-7-10
B.7-4	Primary copper processing facilities	B-7-12
B.7-5	Radionuclide concentrations in copper materials	B-7-16

LIST OF TABLES
(Continued)

<u>Table No.</u>		<u>Page No.</u>
B.7-6	Selected uranium bearing metalliferous deposits in Arizona	B-7-17
B.7-7	Domestic titanium tetrachloride producers	B-7-23
B.7-8	Domestic iron and steel producers	B-7-27
B.7-9	Special wastes generated by ferrous metals facilities in 1988	B-7-30
B.7-10	Distribution of air-cooled iron blast furnace slag among its various applications in 1988	B-7-31
B.7-11	Distribution of steel furnace slag among its various applications in 1988	B-7-32
B.7-12	Primary lead processing facilities in the U.S.	B-7-34
B.7-13	Estimated amount of waste generated by the mining and beneficiation of metal ores in 1980	B-7-37
B.7-14	Estimated slag volumes generated during 1988 from processing raw ores to produce primary metals	B-7-38
B.7-15	Uses of mine waste and tailings	B-7-40
B.7-16	Uses of mineral processing slag	B-7-42
B.7-17	Radionuclide source term for mineral processing wastes	B-7-45
B.8-1	Summary of geothermal drilling activity by state from 1981 to 1985	B-8-4
B.8-2	Geothermal plants for electricity generation	B-8-10
D.1-1	Exposure scenarios for diffuse NORM risk assessment	D-1-4
D.2-1	Generic input parameters for diffuse NORM risk assessment	D-2-22
D.2-2	Reference disposal pile parameters and radionuclide concentrations for diffuse NORM risk assessment	D-2-24

LIST OF TABLES
(Continued)

<u>Table No.</u>		<u>Page No.</u>
D.2-3	Site-specific input parameters for diffused NORM risk assessment	D-2-25
D.2-4	Dose and risk conversion factors	D-2-27
D.2-5	Equivalent uptake factors	D-2-30
D.3-1	Worker doses and health effects from storage or disposal of diffuse NORM	D-3-2
D.3-2	Risks from radon inhalation	D-3-3
D.3-3	Individual doses and health effects from storage or disposal of diffuse NORM	D-3-5
D.3-4	Population doses and health effects from storage or disposal or diffuse NORM	D-3-6
D.3-5	Benchmark of methodology for oil and gas scale/sludge	D-3-8
D.3-6	Summary of dominant risks to workers from one year of exposure	D-3-9
D.3-7	Summary of dominant risks to the critical population group from one year of exposure	D-3-11
D.3-8	Summary of cumulative health effects per reference site from one year of exposure	D-3-12
D.3-9	Summary of cumulative health effects in the United States from one year of exposure	D-3-13
E.2-1	Sources and pathways uncertainties ranking	E-1-12

EXECUTIVE SUMMARY

ES.1 INTRODUCTION

The Environmental Protection Agency (EPA), in September 1989, released a draft risk assessment characterizing generation and disposal practices of wastes which contain diffuse levels of naturally-occurring radioactive materials (NORM). Such wastes are typically generated in large volumes of potentially recyclable materials which may contain radioactivity at elevated concentrations. The draft risk assessment report was prepared as an initial step in the development of acceptable standards governing the disposal and re-use of NORM waste and material. Diffuse NORM wastes and material are of such large volumes and relatively low radionuclide concentrations that it was deemed inappropriate to include them within the scope of other proposed rulemaking activities. The draft report indicated that there is a need to further review the data, assumptions, and models used in that report, provide additional information on categories of diffuse NORM waste which were not explicitly addressed, and perform a more detailed risk assessment. This report, prepared in response to these recommendations, presents the results of further characterization efforts and a revised risk assessment analysis.

ES.2 WASTE VOLUME AND ACTIVITY SUMMARY

All soils and rocks are known to contain some amounts of naturally-occurring radioactive material (NORM). The major radionuclides are uranium and thorium, and their respective decay products. One of the decay products is radium (Ra-226) and its daughter products, which are the principal radionuclides of concern in characterizing the redistribution of radioactivity in the environment. Radium is normally present in soil in trace concentrations of about one picocurie per gram (pCi/g). Certain processes, however, tend to reconcentrate or enrich the radioactivity to much higher levels in the resulting waste or by-product material. Such processes include mining and beneficiation, mineral processing, coal combustion and ash generation, and drinking water treatment, among others. Some of

the NORM wastes or materials are generated in large quantities and typically are disposed or stored at the point of generation. At times, however, NORM materials and wastes are used in various applications which may result in unnecessary radiation exposures, potential adverse health effects, and environmental contamination.

NORM waste generation and disposal practices are characterized in this report for eight NORM sectors. The largest inventories of NORM waste are associated with mineral processing, phosphate rock production, uranium mining, and coal combustion from utility and industrial boilers. Each of these processes generates large volumes of waste with annual production rates of several million metric tons. Over the next 20 years, these NORM sectors will generate significant waste inventories ranging from about 1 to 20 billion metric tons. Smaller amounts of wastes are generated by the petroleum industry (oil and gas pipe scale), geothermal energy production, and by drinking water treatment facilities. Phosphate fertilizers, while not a waste, are included in this analysis because of their elevated radium concentrations. It is estimated that about 100 million metric tons of fertilizers will be applied to agricultural fields over the next 20 years.

The following presents a summary of NORM waste generation practices, 20-year waste or material inventories, and average Ra-226 concentrations, see Table ES-1. An overview of each NORM sector, current waste or material generation rates, and radiological properties is given below. Utilization practices are discussed in the next subsection.

ES.2.1 Uranium Mining Overburden

The uranium industry currently generates about 37 million metric tons (MT) of overburden per year, based on an average of the past four years. The total inventory of unreclaimed overburden is estimated to be 3.1 billion MT. Much of this waste consists of soil and rock which has been removed to uncover underlying uranium deposits. Uranium overburden is used only in a limited number of applications, typically for backfilling mined out areas and to construct site roads. At times, the overburden may contain low grade-ore, which is not suitable for milling. Overburden material, even when mixed with low grade-ore, may contain Ra-226 at relatively high concentrations, typically on the order of several tens

Table ES-1. 20-year NORM waste inventory and concentration^a

Material or Waste Stream	20-Year Waste Inventory^b	Average Ra-226 Concentration^c	Addressed in Chapter
Uranium Mining Overburden	740 mil. MT	23.7 pCi/g	B.1
Phosphate Waste	800 mil. MT	33 pCi/g	B.2
- Phosphogypsum	(800 mil. MT)	(33 pCi/g)	
- Slag	(60 mil. MT)	(35 pCi/g)	
- Scale	(3,000 m ³)	(1,000 pCi/g)	
Phosphate Fertilizers	100 mil. MT	8.2 pCi/g	B.3
Coal Ash	2.0 bil. MT	3.7 pCi/g	B.4
- Fly ash	(1.5 bil. MT)	(3.9 pCi/g)	
- Bottom ash and slag	(520 mil. MT)	(3.1 pCi/g)	
Petroleum Production Scale and Sludge	8.3 mil. MT	155 pCi/g	B.5
Drinking Water Treatment	6.0 mil. MT	16 pCi/g	B.6
- Sludges	(5.1 mil. MT)	(16 pCi/g)	
- Radium selective resins	(840 th. MT)	(35,000 pCi/g)	
Mineral Processing	20 bil. MT	35 pCi/g	B.7
Geothermal Wastes	1.4 mil. MT	160 pCi/g	B.8

a See text for details and assumptions both here and in the preceding subsections.

b The amounts of waste shown here only include the estimated 20-year waste inventory and not the total inventory to date. Units are: bil., billion; mil., million; MT, metric ton, which equals 1,000 Kg or 1.1 short ton.

c Average Ra-226 concentrations are shown for comparative purposes. The risk assessment, however, considers other radionuclides, such as uranium, thorium, and their decay products. Concentrations shown in parentheses are included for illustrative purposes. These values are not used in the risk assessment. See each respective subsection for details.

of pCi/g. For the purpose of this report, the average Ra-226 concentration in overburden waste is assumed to be 23.7 pCi/g.

ES.2.2 Phosphate Waste

It is estimated that the current inventory of phosphogypsum waste is 8 billion MT. The yearly phosphogypsum generation rate has averaged nearly 40 million MT since 1984. An additional 800 million MT of phosphogypsum will be added to the existing inventory over the next 20 years. Phosphogypsum is a by-product material generated during the production of phosphoric acid. Essentially all of the phosphogypsum is stored in waste piles, described as stacks. Only a very small fraction of the phosphogypsum that is produced yearly is put to use, e.g., applied as a soil conditioner. The presence of radium in phosphate rock is known to vary from low concentrations that are nearly identical to those found in soils to levels as high as 60 pCi/g. Elemental phosphorous plants, which use phosphate rock as feedstock, produce a waste called slag. Slag is a vitrified waste resulting from processing phosphate rock in high temperature furnaces. The resulting waste is also high in radium (10 to 60 pCi/g). Slag material has been used in the past as an aggregate in making roads, streets, pavements, residential structures, and buildings. For the purpose of this report, an average Ra-226 concentration of 33 pCi/g is assumed for both waste forms, phosphogypsum and slag.

ES.2.3 Phosphate Fertilizers

In the contest of this report, phosphate fertilizers are not assumed to be waste. The yearly consumption of fertilizers has averaged 4.8 million MT over the past nine years. For the purpose of this report, it is estimated that 5 million MT will be used yearly during the next 20 years. The total amount of fertilizers applied in agricultural fields during the next 20 years is, therefore, assumed to be 100 million MT. Fertilizer application rates are known to vary depending upon the type of crops and soils. A typical phosphate fertilizer application rate is 40 Kg per hectare. Fertilizers are available in different blends with varying concentrations of nitrogen, phosphate, and potassium. In fact, there are over 100 blends. Fertilizers have varying Ra-226 concentrations (5 to 33 pCi/g) depending upon the type of blend and origin of the phosphate rock. The average Ra-226 concentrations in fertilizers is

assumed to be 8.2 pCi/g for the purpose of this assessment. The resulting incremental Ra-226 soil concentration is only on the order of 0.002 pCi/g for 20 years of repeated fertilizer application.

ES.2.4 Fossil Fuels - Coal Ash

Utility and industrial boilers are estimated to generate about 60 million MT of coal ash per year. Of this total amount, nearly 17 million MT are used in a variety of applications. The total amount of coal ash which will be generated over the next 20 years is estimated to be 2.0 billion MT. Coal ash is primarily being used as an additive in concrete, as a structural fill, and for land amendment. The presence of radium in coal is known to vary over two orders of magnitude depending upon the type of coal and region from which it has been mined. The amount of ash generated during combustion is primarily dependent upon the mineral content of the coal and type of boiler. Coal ash generally consists of fly ash, bottom ash, and boiler slags. Ra-226 concentrations in coal may be as low as a fraction of pCi/g to as high as 20 pCi/g. For the purpose of this report, the average coal ash Ra-226 concentration is assumed to be 3.7 pCi/g.

ES.2.5 Oil and Gas Production Scale and Sludge

The types of waste generated by the petroleum industry include pipe scale, sludge, and equipment or components contaminated with Ra-226. It is estimated that the industry generates about 360,000 cubic meters of such waste yearly. The 20-year inventory is assumed to be 4.6 million cubic meters of 8.3 million metric tons. Field surveys have shown that petroleum pipe scale may have very high Ra-226 concentrations, up to 40,000 pCi/g. Some of this waste is retained in oil and gas production equipment, while some of the scale and sludge is removed and stored in drums. The industry disposes of scale and sludge wastes removed from oil and gas production equipment and also discards associated contaminated components. It is difficult to estimate the volume and actual radioactivity levels of discarded equipment since there is little or no information characterizing internal contamination levels. The complex geometry and internal structures of such equipment makes this characterization

difficult. For the purpose of this report, it is assumed that typical scale and sludge Ra-226 concentration is 155 pCi/g.

ES.2.6 Water Treatment Sludge

It is estimated that waste supply systems generate a yearly total of 3.1 million MT of waste, including sludge and other waste forms as well. It is thought that about 700 water utilities generate 260,000 MT of NORM waste yearly. The 20-year inventory is assumed to be 6 million MT, including sludge, and spent resin and charcoal beds. Much of this waste is disposed in landfills, lagoons, and applied in agricultural fields. Water treatment wastes are thought to be of low Ra-226 concentrations, which may be not much different than those found in typical soils. However, some water supply systems, primarily those relying on groundwater sources, may generate sludge with much higher Ra-226 levels. Furthermore, some water treatment systems are more effective than others in retaining naturally-occurring radionuclides. For example, the highest Ra-226 concentrations are found in ion-exchange resin beds, while lower concentrations occur in sludge from lime, soda-lime, and filtration systems. Water supply systems which rely on ion-exchange treatment are comparatively fewer in number. The bulk of the waste is believed to be in the form of sludge. For the purpose of this report, it is assumed that the average Ra-226 concentrations in such waste is 16.0 pCi/g.

ES.2.7 Metal Mining and Processing Waste

The metal mining and processing industry generates about 1 billion MT of waste yearly, excluding phosphate and asbestos related wastes. Accordingly, the 20-year inventory is assumed to be 20 billion MT. It has been estimated that the total waste inventory since the turn of the century is nearly 50 billion MT. Much of this waste is stored on site or near the point of generation. Most of the mineral processing wastes have been used only in a limited number of applications, typically for backfilling mined out areas and to construct site roads. Some of the wastes, however, are in fact stockpiles which are processed several times to extract additional minerals. Although the bulk of the waste is of low radium concentration, about one percent, mainly from monazite sands, zircon sands, ilmenite, and

columbium, have higher radium levels. Mineral processing wastes, for metals such as lead, iron, aluminum, and copper, generate large volumes of waste with extremely variable Ra-226 concentrations. The Ra-226 concentration assumed in this report is 35 pCi/g.

ES.2.8 Geothermal Energy Production Waste

Geothermal energy currently makes a relatively minor contribution to total U.S. energy production. The primary geothermal development sites in the U.S. are the Geysers, in Sonoma County in northern California, and the Imperial Valley in southern California. The only significant NORM-contaminated wastes from geothermal power production are the solid wastes originating from the treatment of spent brines. Very limited data exists from which to characterize the volumes and radionuclide concentrations of these wastes. The vapor resources at the Geysers are characterized by a very low dissolved solids content. However, the hot saline fluids from Imperial Valley reservoirs may have a dissolved solids content approaching 30 wt percent. For this assessment, the estimated NORM waste volumes and radionuclide concentrations are based on limited information available characterizing Imperial Valley geothermal wastes. The estimated 20-year waste volume for this NORM section is 800,000 m³ or 1.4 million MT. The estimated average Ra-226 concentration in this waste is 160 pCi/g.

ES.3 PAST AND CURRENT PRACTICES AND EXPOSURE POTENTIAL

There have been a number of cases where the improper disposal of NORM wastes has resulted in increased levels of direct gamma exposure to individuals. In Montclair, New Jersey, radium contaminated soil caused higher than normal direct gamma radiation exposure levels. The use of elemental phosphorus slag to construct roads in Pocatello, Idaho has resulted in a doubling of the natural background radiation levels in some areas. In Mississippi, the use of pipes contaminated with radium scale in playgrounds and welding classes has resulted in some unnecessary radiation exposures to students using that equipment.

Several forms of diffuse NORM wastes are being disposed or used in a variety of manners. Phosphate waste is placed in large stacks where they are produced, with some of the waste subsequently being used for agricultural or construction purposes. In the past, homes have been built over land containing phosphogypsum waste. Uranium mining overburden is piled and stabilized where it is mined, with little or no subsequent use.

Coal ash is placed in on-site storage ponds, surface impoundments, and sanitary landfills, as well as being reused in road construction, embankments, and in cement aggregates. Studies are currently taking place on the potential use of fly ash in wallboard which may be used in residential and commercial structures. Water treatment plant residues are placed in ponds, sanitary landfills, or spread on agricultural soils. Phosphate fertilizers are, of course, spread on agricultural lands.

Mineral processing wastes are generally disposed in tailings ponds or used to construct dams, dikes, or embankments. Small amounts of waste have been used offsite for backfill, aggregate production, or for road building. Some mineral processing wastes have been used to make wallboard and concrete. Oil and gas pipe scale from the petroleum industry, which is being studied at greater length, is mostly stored until a proper disposal method can be identified. In past practices, however, much of the oil and gas scale has been dumped into nearby surface waters or collection ponds. Some radium contaminated piping has been donated to schools or other organizations.

The contamination of groundwater from NORM wastes has occurred in a few instances. In most cases, however, radium is relatively immobile and does not move into groundwater very quickly. An exception to this may be mineral processing wastes containing radium in the chloride form, which appears to have a much higher mobility. In the past, groundwater contamination has been associated with uranium mining waste and from the improper disposal of radium pipe scale.

Many of these disposal methods or uses may result in negligible exposures to individuals. However, improper use or disposal of these wastes can result in significant contamination of the environment, as well as having adverse impacts on individual and public health. In fact, the unregulated use or disposal of waste containing elevated concentrations of radium has resulted in contamination of soil and groundwater, and

exposures to individuals. In addition, as waste materials are being used, further research is taking place to identify new applications, in turn possibly leading to additional individual exposures.

ES.4 RISK ASSESSMENT ANALYSES

The risk assessment analysis addresses several pathways for exposures to disposal site workers, members of the critical population group (CPG), and the general population for each of the eight NORM waste sectors. The exposure scenarios evaluated for each NORM sector are shown in Table ES-2.

Estimated dominant risks to workers at NORM storage and disposal sites and to members of the CPG are summarized in Table ES-3. For site workers the dominant exposure pathway is indoor radon inhalation to office workers. For office workers, the 70-year lifetime risks from one year of radon inhalation are estimated to range from $9.3\text{E-}02$ for the geothermal waste sector to $1.2\text{E-}04$ for landfill disposal of water treatment sludge. For exposure pathways other than radon inhalation, the dominant health risks result from direct gamma exposure of disposal pile workers. Risks from direct gamma exposure are estimated to be two or three orders of magnitude smaller than risks from indoor radon inhalation. Seventy-year lifetime risks from direct gamma exposure range from $2.5\text{E-}04$ for the oil and gas scale/sludge NORM sector to $2.4\text{E-}09$ for workers on fields repeatedly fertilized with phosphate fertilizer.

Indoor exposure to radon gas by a person living on an abandoned NORM disposal site is estimated to be the dominant exposure pathway for members of the CPG. For this pathway, the 70-year lifetime risks from one year of exposure to indoor radon range from $3.1\text{E-}01$ for the geothermal waste sector to $3.0\text{E-}06$ for a field repeatedly fertilized with phosphate fertilizer. For exposure pathways other than radon inhalation the dominant CPG health risks are from direct gamma exposure, either to a person who lives on an abandoned disposal site or to a person exposed to NORM in building materials. For direct gamma exposure, the 70-year lifetime risks from one year of exposure range from $6.7\text{E-}03$ for mineral processing waste to $1.1\text{E-}08$ for a field repeatedly fertilized with phosphate fertilizer. For

Table ES-2. Exposure scenarios for diffuse NORM risk assessment.

Exposure Scenario	Uranium Overburden	Phosphate Waste	Phosphate Fertilizer	Coal Ash	Water Treatment Sludge – Fertilizer	Water Treatment Sludge – Landfill	Mineral Processing Waste	Oil & Gas Scale/Sludge	Geothermal Waste
Worker									
Direct Gamma Exposure	X	X	X	X	X	X	X	X	X
Dust Inhalation	X	X	X	X	X	X	X	X	X
Indoor Radon Inhalation	X	X		X		X	X	X	X
Onsite Individual									
Direct Gamma Exposure	X	X	X	X	X	X	X	X	X
Indoor Radon Inhalation	X	X	X	X	X	X	X	X	X
Member of CPG									
Direct Gamma Exposure	X	X	X	X	X	X	X	X	X
Inhalation of Contaminated Dust	X	X	X	X	X	X	X	X	X
Downwind Exposure to Radon	X	X	X	X	X	X	X	X	X
NORM in Building Materials		X		X			X		
Ingestion of Drinking Water from a Contaminated Well	X	X	X	X	X	X	X	X	X
Ingestion of Foodstuffs Contaminated by Well Water	X	X	X	X	X	X	X	X	X
Ingestion of Foodstuffs Contaminated by Dust Deposition	X	X	X	X	X	X	X	X	X
Ingestion of Foodstuffs Grown on Repeatedly Fertilized Soil			X		X				
General Population Near Sites									
Downwind Exposure to Resuspended Particulates	X	X	X	X	X	X	X	X	X
Downwind Exposure to Radon	X	X	X	X	X	X	X	X	X
Ingestion of River Water Contaminated Via the Groundwater Pathway	X	X	X	X	X	X	X	X	X
Ingestion of River Water Contaminated by Surface Runoff									
Ingestion of Foodstuffs Grown on Repeatedly Fertilized Soil			X		X				

Table ES-3. Summary of dominant risks to individuals from storage or disposal of diffuse NORM wastes.

NORM Waste Sector	Disposal Site Worker (Health Effects)^a		Member of CPG (Health Effects)^a	
	Exposure Pathways Except Radon Inhalation	Radon Inhalation	Exposure Pathways Except Radon Inhalation	Radon Inhalation
Uranium Overburden	2.5E-05	1.8E-02	1.1E-04	6.0E-02
Phosphate Waste	3.8E-05	1.2E-02	4.4E-03	3.9E-02
Phosphate Fertilizer	2.4E-09	—	1.1E-08	3.0E-06
Coal Ash	6.3E-06	1.4E-04	7.3E-04	4.5E-04
Water Treatment Sludge - Fertilizer	8.8E-07	—	4.0E-06	1.0E-03
Water Treatment Sludge - Landfill	3.1E-07	1.2E-04	1.4E-06	3.8E-04
Mineral Processing Waste	5.9E-05	2.7E-02	6.7E-03	8.9E-02
Oil and Gas Scale/Sludge	2.5E-04	2.1E-02	1.2E-03	7.0E-02
Geothermal Waste	2.6E-05	9.3E-02	1.2E-04	3.1E-01

^a The 70-year lifetime risk of a fatal cancer from one year of exposure.

members of the CPG, health risks from direct gamma exposure are estimated to be one to three orders of magnitude smaller than health risk from indoor radon inhalation.

Estimated population health effects (e.g., cumulative health effects to persons living and working offsite) are summarized in Table ES-4. The largest number of cumulative health is associated with the coal ash NORM sector, in part because of the large number of sites needed to deplete the 20-year inventory. Two NORM sectors -- coal ash and mineral processing waste -- have total population health effects greater than unity. The NORM sectors with the lowest total population health effects -- water treatment sludge, oil and gas scale/sludge, and geothermal waste -- each have less than 0.1 health effects from one year of exposure.

The risk assessment results suggest that a relatively moderate number of health effects could result from the improper use or disposal of diffuse NORM wastes. These results are based only on the total NORM waste inventory anticipated to be generated over the next 20 years. Should the total inventory of NORM waste accumulated to date to be used instead, the total number of health effects would increase significantly. However, this assumption would most likely be unrealistic because the accumulated waste inventory is not in a readily accessible and useable form, as postulated in this report, and currently there is no outlet which would allow that much NORM waste to be recycled.

Given the uncertainties associated with waste volumes, radionuclide concentrations, and exposure pathway models and parameters, it is estimated that the results of this risk assessment analysis are within a factor of 3 of results that might be obtained by using more sophisticated computer codes. In general, it is suspected that the variability of the results is asymmetric, in the sense that the degree of conservatism is more pronounced on the lower range of the input parameters and assumptions than on the higher end. Accordingly, depending upon a specific input parameter or assumption, the results may reveal a still greater degree of variability. Finally, it should be noted that changing a parameter does not always yield results that are directly proportional since competing factors may nullify an increase in a specific parameter.

Given that these results are based on a number of assumptions, some better defined than others, these estimates are still uncertain. The results imply, however, that the number

Table ES-4. Summary of population health effects from storage or disposal of diffuse NORM wastes.

NORM Waste Sector	Number of Sites for 20-year Inventory	Number of Health Effects^a	
		Generic Site	Nationwide for 20-year Inventory
Uranium Overburden	1.4E+01	1.7E-02	2.4E-01
Phosphate Waste	1.5E+01	3.5E-02	5.2E-01
Phosphate Fertilizer	9.4E+05	9.8E-07	9.2E-01
Coal Ash	1.3E+03	8.9E-03	1.2E+01
Water Treatment Sludge - Fertilizer	4.4E+02	1.6E-04	7.0E-02
Water Treatment Sludge - Landfill	2.3E+02	7.9E-06	1.8E-03
Mineral Processing Waste	6.7E+02	2.6E-03	1.7E+00
Oil and Gas Scale/Sludge	1.0E+01	5.6E-03	5.6E-02
Geothermal Waste	2.0E+00	7.6E-03	1.5E-02

^a Number of excess fatal cancers (70-year lifetime risk) expected in the exposed population as a result of one year of exposure.

of potential health effects may be significant enough to warrant additional evaluation of NORM waste generation and disposal practices for some of the NORM waste sectors.

ES.5 REGULATORY CONTROL OPTIONS

The Atomic Energy Act of 1954, and subsequent amendments, is the basic framework for the regulatory control of radioactivity and radioactive material. The Act of 1954 and administrative reorganizations, give the primary regulatory responsibility to the U.S. Nuclear Regulatory Commission (NRC). The NRC has granted some of these responsibilities to states, under the Agreement State Program. The states, in addition to the responsibilities granted by the NRC, have in some cases adopted additional regulations. In addition to the regulations of the NRC and agreement states, several federal agencies (e.g., Department of Transportation, Department of Labor, and Environmental Protection Agency) have regulatory authority related to pertinent aspects of radiation, radiation protection for workers, and radioactive materials shipment and disposal.

NORM materials are not covered by the Atomic Energy Act of 1954 and are generally not specifically covered by most existing regulations. Although they are covered by some state regulations, there are presently no universally applicable regulations for NORM materials. The Conference of Radiation Control Program Directors (CRCPD) has prepared draft regulations to be considered by the states. These draft regulations specify criteria in terms of concentration and surface contamination limits.

Some states have taken the lead and are in the process of drafting regulations to address specific problems. For example, the State of Louisiana has promulgated emergency regulations, similar to the draft regulations of the CRCPD in 1989. The Louisiana regulations identify the criteria for unrestricted release as surface contamination criteria similar to the American National Standards Institute recommendations. The State of Texas has issued an interim policy regarding the handling and disposal of contaminated oil and gas pipe scale and equipment.

The improper use or disposal of diffuse NORM wastes has led to circumstances resulting in contamination events and unnecessary exposures. Such events have included groundwater contamination, direct radiation exposures to individuals, and increased levels of radon gas in homes built over contaminated materials. In view of the results of the risk assessment, it can be seen that there exists a range of potential health impacts associated with the improper use or disposal of NORM wastes. It is clear that a significant number of health effects and high risks could occur for a limited number of individuals in exposed populations. There is still some uncertainty about many of the assumptions used in the analyses. Even with these uncertainties, however, such occurrences suggest that the disposal of large quantities of diffuse NORM waste may warrant the implementation of some regulatory controls.

One option for regulating the disposal of NORM wastes would be the use of RCRA. Based on the potential health impact associated with radium-226, NORM waste could be designated as a RCRA hazardous waste. As this would require disposal in RCRA hazardous waste disposal facilities, this may not be a particularly feasible option due to the tremendous volumes of NORM waste being generated.

Another option, under RCRA, would be to use Subtitle D requirements for regulating disposal. This option is being studied by EPA, although with no regulatory action planned at this time. In addition, use of Subtitle D is less desirable, since Subtitle D lacks federal enforcement capabilities.

There is a drawback in using RCRA in that RCRA only governs waste disposal. Since much of the health impact is due to the improper use of NORM waste, RCRA could not be used to control that aspect since it would be considered recycling and not waste disposal. For this reason, and because of the lack of past regulatory action for this class of waste under RCRA, it is appropriate to consider other regulatory options.

There are currently EPA regulations being considered which apply to the disposal of higher concentrations of NORM wastes (greater than 2,000 pCi/g). The diffuse NORM wastes, however, are of such large volume and relatively low radionuclide concentrations that it was deemed inappropriate to include these wastes within the scope of the rulemaking. These regulations are being prepared under the authority of Section 6 of TSCA, which could

also be used to regulate diffuse NORM wastes. Under Section 6, materials found to present unreasonable risk to the public can be controlled in a variety of ways, including requirements on disposal, manufacture, distribution in commerce, and the use of warning labels and record keeping.

Since the greatest health impact associated with diffuse NORM wastes appears to be associated with its improper use and disposal, Section 6 of TSCA would allow the EPA to prohibit certain uses of the waste that were found to be improper, such as its use as fill material or incorporated in wallboard or other types of construction materials. Section 6 could also be used to regulate the disposal of the waste if it were determined to be necessary for public health reasons. In addition to the control options available under Section 6, other sections of TSCA allow the Administrator to designate other federal agencies to help in implementing and enforcing the regulations, if it is found that this approach is the most efficient way to regulate NORM waste, while placing the least burdensome requirements on waste generators. Because of the inherent flexibility of the TSCA regulations, this approach may be the optimal way to establish the proper regulatory controls for the use and/or disposal of NORM waste.

A. INTRODUCTION

Radioactive materials can be classified under two broad headings: man-made and naturally-occurring radioactive materials. Man-made radionuclides are produced by splitting atoms in nuclear reactors or by bombarding atoms with subatomic particles in accelerators. Examples of man-made radionuclides include cobalt-60, strontium-90, and cesium-137. Naturally-occurring radionuclides include primordial radionuclides that are naturally present in the rocks and minerals of the earth's crust and cosmogenic radionuclides produced by interactions of cosmic nucleons with target atoms in the atmosphere and in the earth. Examples of cosmogenic radionuclides include carbon-14 and tritium (hydrogen-3).

The principal primordial radionuclides are isotopes of heavy elements belonging to the radioactive series headed by the three long-lived isotopes uranium-238 (uranium series), uranium-235 (actinium series), and thorium-232 (thorium series). These three decay series are shown in Figures A.1-1 to A.1-3. All three of these series have numerous radionuclides in their decay chains before reaching a stable end point, lead. At background concentrations, the naturally-occurring radionuclides in the uranium, actinium, and thorium series contribute about one-half of the natural background external radiation, and over 80 percent of the background including radon, to which all humans are continuously exposed.

NORM (naturally-occurring radioactive material) consists of material containing isotopes belonging to the uranium, actinium, and thorium series. The principal radionuclide of concern in NORM is radium-226, a member of the uranium series, which is present in natural soils in concentrations of about 1 pCi/g. However, NORM radioisotopes may be present in different materials in varying concentrations, and some NORM wastes may have radium-226 concentrations that are much higher than 1 pCi/g, and may be as high as hundreds of thousands of pCi/g.

The ultimate sources of the primordial radionuclides in the environment are the earth's crust and its underlying plastic mantle. Movement of material or heat, or both, from the mantle to the crust, and heat from radioactive decay in the crust, have caused a reorganization of the chemical elements in the crust tending from homogeneity toward

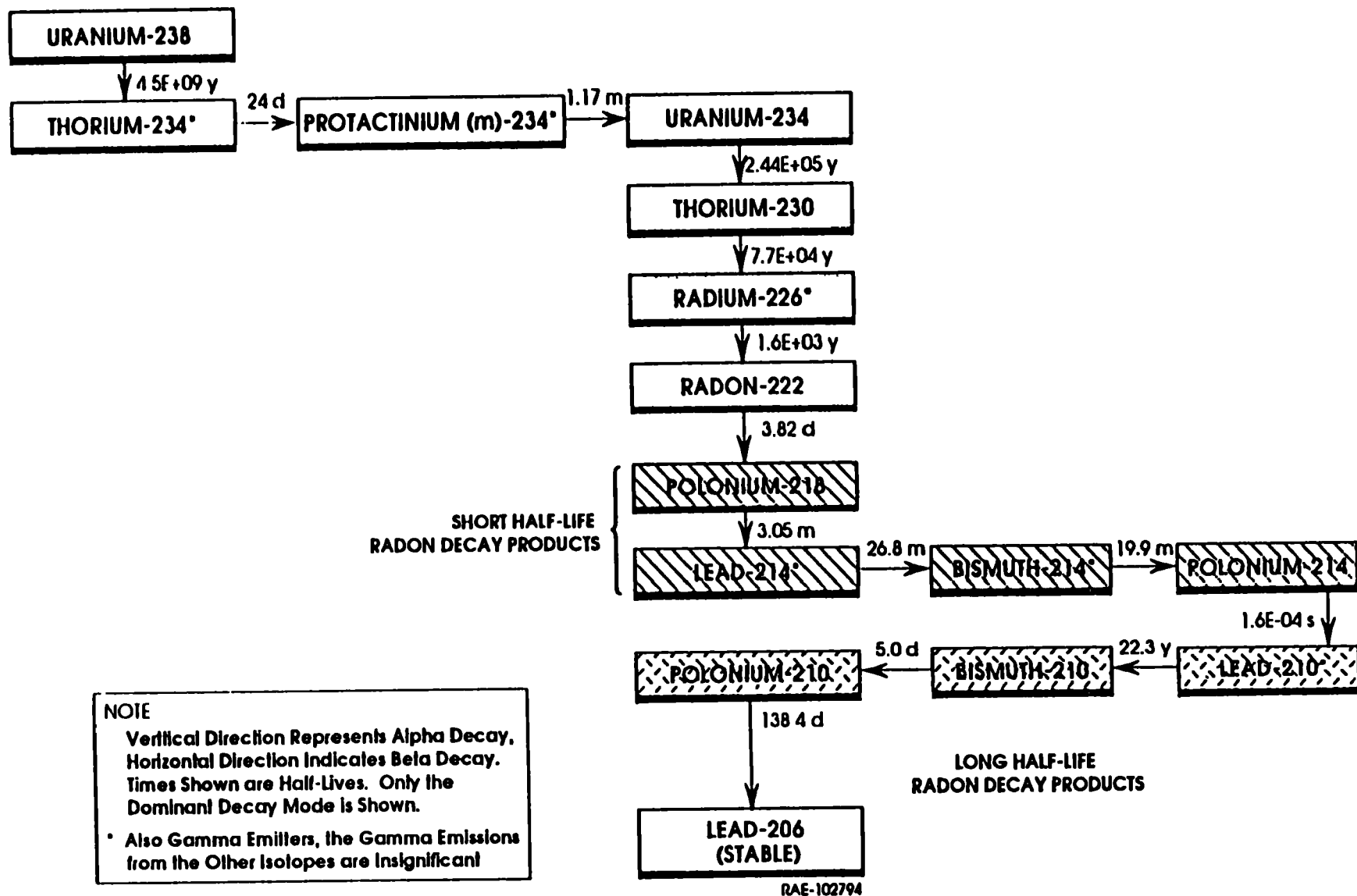


Figure A.1-1. Uranium decay chain.

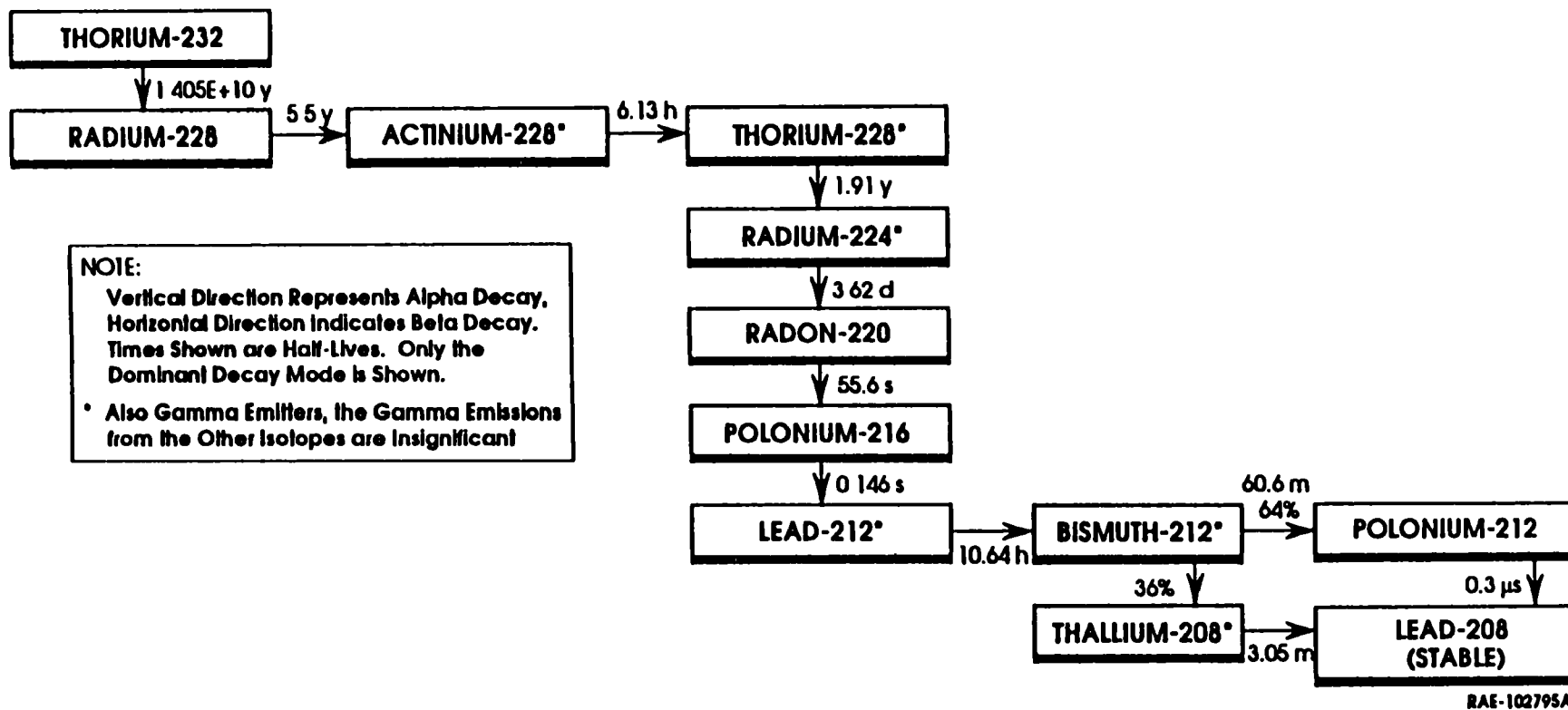


Figure A.1-2. Thorium decay chain.

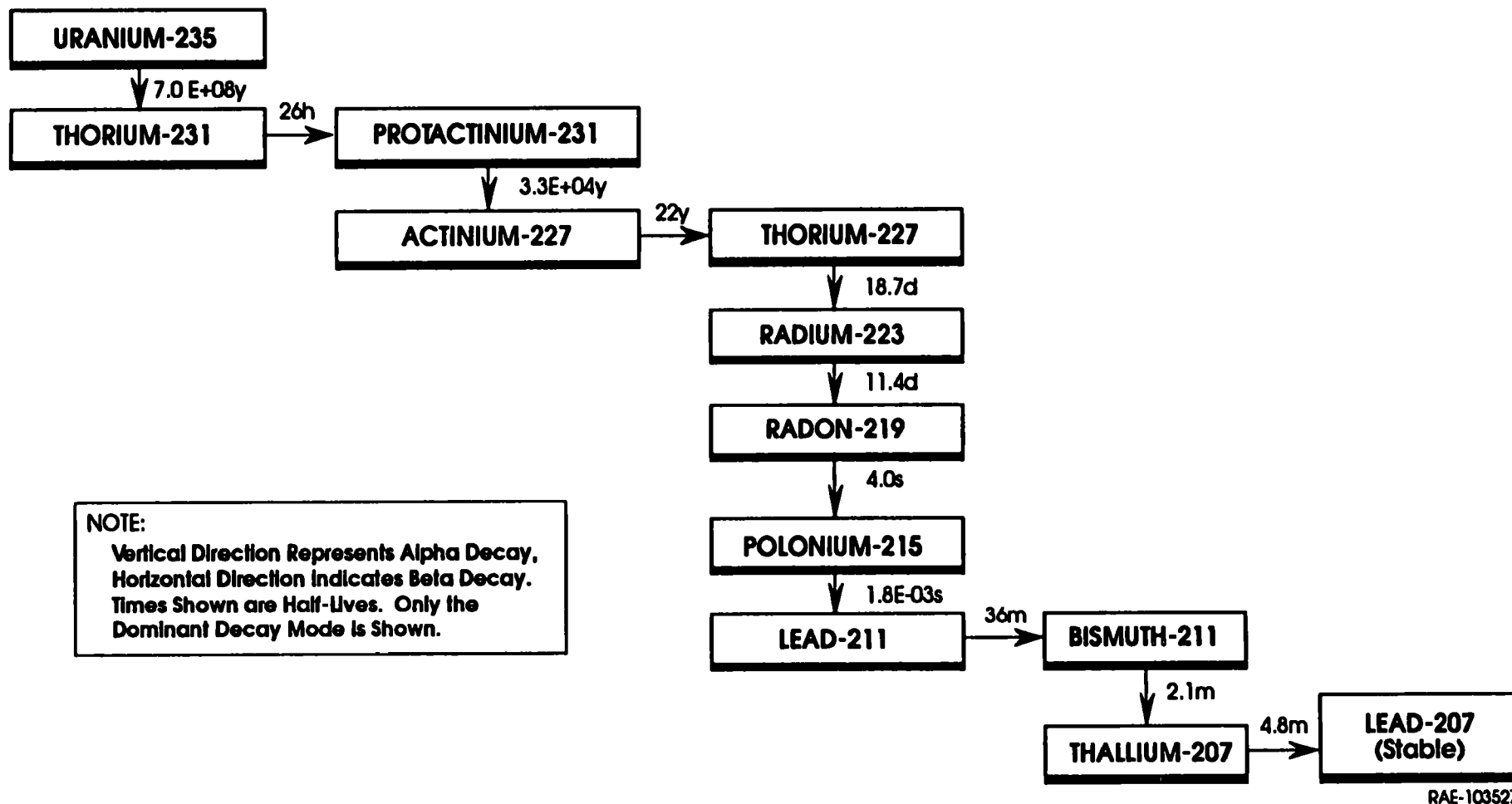


Figure A.1-3. Actinium series decay chain.

heterogeneity. Redistribution has also occurred as a result of weathering and sedimentation. As a consequence of these processes, the uranium and thorium series nuclides have tended to concentrate in certain minerals and certain geologic formations. For example, uranium in significantly elevated concentrations is associated with phosphate ores in three major locations in the U.S. These locations are southeastern Idaho and parts of neighboring states, central Florida, and central Tennessee and northern Alabama. Radionuclides from the uranium and thorium series are also associated in widely ranging proportions in the crude oil and brine extracted from underground petroleum reservoirs.

NORM wastes are the radioactive residues from the extraction and purification of minerals, petroleum products, or other substances obtained from parent materials that may contain elevated concentrations of primordial radionuclides. Each year, hundreds of millions of metric tons of NORM waste are generated from a wide variety of processes, ranging from uranium and phosphate mining to municipal drinking water treatment. Processes that produce NORM wastes analyzed in this study include uranium mining, phosphate and elemental phosphorus production, phosphate fertilizer production, coal ash generation, oil and gas production, drinking water treatment, metal mining and processing, and geothermal energy production. During mining and beneficiation, mineral processing, oil and gas extraction, or various other processes, primordial radionuclides present in the parent materials can become concentrated in the wastes. This results in radionuclide concentrations in NORM wastes that are often orders of magnitude higher than in the parent materials.

The exposure to individuals from NORM wastes occurs in three main ways. The first is associated with the normal disposal of the waste in piles or stacks. This type of disposal can lead to groundwater contamination and to airborne releases of radioactive particulates and radon. The second is from the improper use and/or disposal of these wastes, such as for soil conditioning or fill dirt around homes. This can lead to build-up of radon gas in homes, direct exposure to individuals located nearby, contamination of soil and the crops growing in that soil, and groundwater contamination. The third way is the improper use of NORM waste in materials, such as concrete aggregate and wallboard. This can lead to direct external exposures to individuals and to increased levels of radon in homes.

Most radionuclides are regulated under the authority of the Atomic Energy Act (AEA). The AEA, however, excludes all NORM, except high grade uranium and thorium ore, any materials containing uranium and thorium, and uranium mill tailings. The Environmental Protection Agency (EPA) is currently developing regulations for the disposal of higher concentration (above 2 nanocuries/gram) NARM (naturally-occurring and accelerator-produced radioactive materials) wastes under the authority of the Toxic Substances Control Act (TSCA) (EPA88). For the lower concentration materials, termed diffuse NORM wastes, no federal regulations currently exist. Due to the large volumes of diffuse NORM wastes that are generated each year, and the potential risk of individual exposures associated with the improper use and disposal of these wastes, it is appropriate for the EPA to consider developing controls on the use and disposal of diffuse NORM wastes.

The EPA, in September 1989, released a draft risk assessment characterizing generation and disposal practices of diffuse NORM wastes. The draft risk assessment report was prepared as an initial step in the development of acceptable standards governing the disposal and re-use of NORM waste and material. The draft report indicated that there is a need to further review the data, assumptions, and models used in that report, provide additional information on categories of diffuse NORM waste which were not explicitly addressed, and perform a more detailed risk assessment. This report, prepared in response to these recommendations, presents the results of further characterization efforts and a revised risk assessment analysis.

In the following chapters, the major waste generating processes for eight NORM waste sectors are described and the radioactivity concentrations and volumes of these wastes are estimated. Also discussed are current practices for the wastes, regarding their use and disposal. A risk assessment is performed which addresses several pathways for exposures to individuals and the general population for each of the eight NORM waste sectors. The exposure pathways considered include direct gamma radiation, dust inhalation, downwind dispersion of resuspended particulates and radon, indoor radon inhalation, exposure from building materials that incorporate NORM waste, and ingestion of contaminated water and foodstuffs. The NORM waste sectors analyzed and the exposure scenarios evaluated for each sector are shown in Table A.1-1.

Table A.1-1. Exposure scenarios for diffuse NORM risk assessment.

Exposure Scenario	Uranium Overburden	Phosphate Waste	Phosphate Fertilizer	Coal Ash	Water Treatment Sludge -- Fertilizer	Water Treatment Sludge -- Landfill	Mineral Processing Waste	Oil & Gas Scale/Sludge	Geothermal Waste
<u>Worker</u>									
Direct Gamma Exposure	X	X	X	X	X	X	X	X	X
Dust Inhalation	X	X	X	X	X	X	X	X	X
Indoor Radon Inhalation	X	X		X		X	X	X	X
<u>Onsite Individual</u>									
Direct Gamma Exposure	X	X	X	X	X	X	X	X	X
Indoor Radon Inhalation	X	X	X	X	X	X	X	X	X
<u>Member of CPG</u>									
Direct Gamma Exposure	X	X	X	X	X	X	X	X	X
Inhalation of Contaminated Dust	X	X	X	X	X	X	X	X	X
Downwind Exposure to Radon NORM in Building Materials	X	X	X	X	X	X	X	X	X
Ingestion of Drinking Water from a Contaminated Well	X	X	X	X	X	X	X	X	X
Ingestion of Foodstuffs Contaminated by Well Water	X	X	X	X	X	X	X	X	X
Ingestion of Foodstuffs Contaminated by Dust Deposition	X	X	X	X	X	X	X	X	X
Ingestion of Foodstuffs Grown on Repeatedly Fertilized Soil			X		X				
<u>General Population Near Sites</u>									
Downwind Exposure to Resuspended Particulates	X	X	X	X	X	X	X	X	X
Downwind Exposure to Radon	X	X	X	X	X	X	X	X	X
Ingestion of River Water Contaminated Via the Groundwater Pathway	X	X	X	X	X	X	X	X	X
Ingestion of River Water Contaminated by Surface Runoff									
Ingestion of Foodstuffs Grown on Repeatedly Fertilized Soil			X		X				

Risks from exposure to NORM waste are evaluated for site workers, onsite individuals, members of the critical population group (CPG), and the general population. These exposed persons are identified and described in the following paragraphs.

Site workers include disposal pile workers and office workers. The disposal pile worker is an adult employee who works 2,000 hours per year, spending 80 percent of his time on the waste pile. It is assumed that the waste pile is not covered or capped. The worker uses machinery such as a grader or bulldozer which places him one meter above the pile surface and provides some shielding from direct gamma radiation. Exposure pathways for the disposal pile worker include direct radiation and dust inhalation. For direct radiation, a shielding factor of 0.6 is applied to account for the shielding provided by the machinery used by the worker.

The office worker also works 2,000 hours per year in a building located at the disposal site. While in the building, the worker is exposed via the indoor radon inhalation pathway. Although an office building would likely be located at some distance from the disposal pile, to estimate the indoor radon concentration it is assumed that the building is located on the pile. This results in a conservatively high estimate of the radon exposure received by the office worker.

Two exposure pathways are evaluated for a person who is assumed to live on a site which was formerly used for the disposal of diffuse NORM wastes. The exposure pathways analyzed for this "onsite individual" are indoor radon inhalation and direct exposure to gamma radiation. For indoor exposure to radon, the exposure fraction (i.e., the fraction of a year that the person is exposed) is 0.75. For direct exposure to gamma radiation, the equivalent exposure fraction is 0.5. This equivalent exposure fraction takes into consideration the time spent outside plus the time spent inside at a reduced exposure level.

Several exposure pathways are evaluated for a member of the CPG. This person is assumed to be an adult who lives in a house located 100 m from the disposal pile. The person obtains all of his water from a well adjacent to the house. Fifty percent of his foodstuffs are assumed to be grown onsite. For a member of the CPG, the exposure pathways analyzed include direct radiation, inhalation of contaminated dust, downwind exposure to radon, exposure to NORM in building materials, ingestion of contaminated well water,

ingestion of foodstuffs contaminated by well water, ingestion of foodstuffs contaminated by dust deposition, and ingestion of foodstuffs grown on repeatedly fertilized soil. For direct exposure to gamma radiation, contaminated dust inhalation, and downwind exposure to radon, the equivalent exposure fraction is 0.50. This equivalent exposure fraction takes account of the time spent outside plus the time spent indoors at a reduced exposure level.

Several exposure pathways are evaluated for the general population residing near the disposal sites. Population exposure pathways include downwind exposure to resuspended particulates, downwind exposure to radon, ingestion of river water contaminated by groundwater or by surface runoff, and ingestion of foodstuffs grown on repeatedly fertilized soil. For the downwind exposure pathways, the exposed population is assumed to reside within a radius of 80,000 m (50 mi) of the disposal site. For the ingestion pathways the exposed population is assumed to live within a river water "use area" of approximately 1,000 mi².

This report presents a waste characterization and risk assessment for diffuse NORM waste. Chapter B presents the major NORM waste generating sectors and a description of the processes which result in the generation of such wastes. The characterization provides a description of the physical and radiological properties of the waste, waste generation rates, and a 20-year inventory. Also reviewed are current industry or NORM sector practices regarding the use and disposal of such wastes. An overview of past disposal practices and misuse of NORM waste is provided in Chapter C. The risk assessment, presented in Chapter D, focuses on the health impact associated with the uncontrolled disposal and/or use of these wastes. The risk assessment estimates are calculated to provide an insight into the potential health impact associated with NORM waste, to determine whether a more rigorous analysis or more detailed characterization is justified, and to help evaluate the need for future regulatory action. Chapter E provides a summary and conclusion.

CHAPTER A

EPA88 U.S. Environmental Protection Agency, "Low-Level and NARM Radioactive Wastes, Draft Environmental Impact Statement for Proposed Rules, Volume 1, Background Information Document," EPA 520/1-87-012-1, June 1988.

B.1. URANIUM MINING OVERBURDEN

1.1 INTRODUCTION

The uranium mining industry began in the late 1940s primarily for the purpose of producing uranium ore for use in weapons production and nuclear fuel fabrication. The mining of uranium ore by both underground and surface methods produces large amounts of bulk material, including excavated topsoil, overburden, low grade ore and mining spoils. Topsoil is the natural soil overlying the area which is being mined. Overburden, which is beneath the topsoil and overlies the ore deposit, contains limited amounts of natural uranium and its progeny. Overburden materials must be removed in order to expose the underlying ore bodies. Low grade ore material, or subore, contains significant amounts of uranium, but usually does not have a high enough uranium concentration to make milling economically feasible. Mining spoils include low grade ore and other materials excavated during mine exploitation. The quantities of these materials produced during mining depend upon the mining method used and the ore grade. The ore grade is known to vary by type of uranium deposits and mining regions. For example, the ore mined from 1978 to 1987 was reported to have a U_3O_8 concentration that varied from a low of 0.112 percent to a high of 0.336 percent, with an average of 0.162 percent (DOE88, EIA88a).

Waste piles are associated with the larger mines, and surface mines are responsible for the vast majority of the waste materials. The potential for the waste piles to cause exposure to the general public or to become redistributed in the environment depends, in part, on their location and whether they have been stabilized.

In the sections that follow, a description is provided of the uranium mining industry, the properties of uranium overburden materials, and actual and projected amounts of overburden waste materials produced by this NORM sector. This information is used to assess potential exposures to the members of the general public and critical population group, see Chapter D.

1.2 OVERVIEW OF THE URANIUM MINING INDUSTRY

There are 3,592 surface and underground uranium mines located in 18 states in the United States, but only a small number of these are currently operating (EPA83). A summary of the number of surface and underground mines that have produced ore since the inception of the industry is presented in Table B.1-1.

The production of uranium ore by surface and underground mining methods has been on a steady decline since 1980, when the average contract price of U_3O_8 decreased from \$40 to \$26 per pound (EIA88a). In 1982 there were 139 underground mines and 24 surface mines still operating in the United States; currently, only 15 underground mines and two surface mines are in operation (EPA89). Most of the inactive mines (about two-thirds) are surface mines which, to date, have produced over 99 percent of the waste material. Because of the sharp decline in uranium mining and the shift from surface to underground mines in the decade of the 1980s compared to the previous decade, projections of uranium ore production and the associated waste volumes bear little resemblance to the past experience of the uranium mining industry. In addition, the current inventory of unreclaimed mining overburden is projected to decrease as planned reclamation is performed (SCA89).

A summary of uranium ore and U_3O_8 production by the uranium mining industry in the U.S. is presented in Table B.1-2. The production of uranium ore peaked in 1980 when a total of 15.2 million MT of ore, including 9.4 million MT from surface mines and 5.8 million MT from underground mines, was produced. By 1988, uranium ore production had decreased to 1.1 million MT, including 0.63 million MT from surface mines and 0.47 million MT from underground mines (EIA88a).

1.2.1 Surface Mining

The use of surface (open pit) mining methods is most prevalent in Wyoming, New Mexico, south Texas, and in some areas of Colorado and Utah. In surface mining, an open pit is excavated to expose the uranium deposit. After the topsoil is removed and stockpiled nearby, the overburden is removed by the method best suited to the nature of the rock. If

Table B.1-1. Location of surface and underground uranium mine sites in the U.S.^a

State	Surface	Underground
Alaska	0	1
Arizona	135	190
California	13	10
Colorado	268	1,008
Idaho	2	4
Minnesota	0	0
Montana	9	9
Nevada	9	12
New Jersey	0	1
New Mexico	38	177
North Dakota	13	0
Oklahoma	3	0
Oregon	2	1
South Dakota	111	30
Texas	54	0
Utah	391	806
Washington	15	0
Wyoming	242	38
Subtotal:	1,305	2,287
Total:		3,592

a Table adapted from data taken from EPA83.

Table B.1-2. Uranium ore production from 1948 to 1988.^a

Year	Surface Mines^b		Underground Mines^b	
	Ore (MT)	U₃O₈ (MT)	Ore (MT)	U₃O₈ (MT)
1948 ^c	<9.0E+2	<9.1E+1	3.4E+4	9.1E+1
1949 ^d	9.1E+2	<9.1E+1	1.6E+5	4.5E+2
1950	2.1E+4	9.1E+1	2.1E+5	6.4E+2
1951	2.5E+4	1.8E+2	2.9E+5	8.2E+2
1952	5.9E+4	2.7E+2	3.4E+5	9.1E+2
1953	1.6E+5	5.4E+2	5.0E+5	1.5E+3
1954	2.4E+5	8.2E+2	7.6E+5	2.4E+3
1955	3.4E+5	7.3E+2	1.0E+6	3.3E+3
1956	1.1E+6	2.9E+3	1.6E+6	4.7E+3
1957	1.5E+6	3.1E+3	1.9E+6	5.8E+3
1958	2.1E+6	4.9E+3	2.6E+6	7.8E+3
1959	2.0E+6	4.0E+3	4.3E+6	1.2E+4
1960	2.2E+6	4.8E+3	5.1E+6	1.2E+4
1961	2.3E+6	4.8E+3	5.0E+6	1.2E+4
1962	1.6E+6	3.9E+3	4.8E+6	1.2E+4
1963	1.7E+6	4.0E+3	3.7E+6	9.4E+3
1964	1.4E+6	3.1E+3	3.4E+6	9.5E+3
1965	1.1E+6	2.7E+3	2.8E+6	6.7E+3
1966	1.2E+6	2.8E+3	2.7E+6	6.2E+3
1967	1.4E+6	2.9E+3	3.4E+6	6.8E+3
1968	2.1E+6	4.2E+3	3.7E+6	7.3E+3
1969	2.0E+6	4.7E+3	3.4E+6	6.4E+3
1970	2.5E+6	5.4E+3	3.2E+6	6.3E+3
1971	3.0E+6	6.4E+3	2.7E+6	5.4E+3
1972	3.5E+6	7.4E+3	2.3E+6	5.1E+3
1973	4.1E+6	7.8E+3	1.8E+6	4.5E+3
1974	3.8E+6	6.6E+3	2.6E+6	4.6E+3
1975	3.9E+6	6.1E+3	2.5E+6	4.8E+3
1976	4.2E+6	6.2E+3	3.6E+6	6.1E+3

Table B.1-2. Continued.

Year	Surface Mines^b		Underground Mines^b	
	Ore (MT)	U₃O₈ (MT)	Ore (MT)	U₃O₈ (MT)
1977	5.1E+6	6.9E+3	4.3E+6	7.5E+3
1978	7.5E+6	8.7E+3	5.5E+6	8.4E+3
1979	8.8E+6	8.5E+3	4.9E+6	5.7E+3
1980	9.4E+6	9.4E+3	5.8E+6	8.7E+3
1981	7.7E+6	6.4E+3	4.7E+6	7.8E+3
1982	5.0E+6	3.5E+3	2.5E+6	5.6E+3
1983	7.4E+6	e	4.3E+6	e
1984	1.8E+6	1.3E+3	9.3E+5	2.2E+3
1985	8.5E+5	9.1E+2	5.2E+5	2.0E+3
1986	1.3E+5	9.1E+1	6.0E+5	2.9E+3
1987	9.3E+5	e	6.8E+5	e
1988	6.4E+5	e	6.0E+5	e

a Data extracted from Uranium Industry Annual - 1988 (EIA88a).

b Quantities are expressed in metric tons (MT), e.g., 1.1E+6 MT means 1,100,000 metric tons.

c Value is less than 900 MT.

d Value is less than 91 MT.

e For 1983, 1987, and 1988, data for surface and underground mine production totals were not reported separately. Ore quantities are estimated using the average of 3 previous years.

the rock is easily crumbled, it is removed by tractor-mounted ripper bars, bulldozers, shovels, or pushload scrapers. If it is not, drilling and blasting are required. The overburden is then trucked to a nearby waste dump. Occasionally, dikes and ditches are constructed around these waste piles to collect runoff and divert it to sedimentation ponds. Overall, an area of tens of hectares may be covered by stored overburden (EPA83). For example, an areal survey of 10 surface mining sites located in New Mexico (8) and Wyoming (2) indicated that the disturbed areas varied from 1.1 to 154 hectares, with an average of 44 hectares per site (1 hectare is equivalent to 2.5 acres).

At some sites, as mining progresses, the overburden is used to backfill mined-out areas of the open pit. In these cases, when an area is completely backfilled, it is graded to conform to the surrounding topography and to restore the natural drainage patterns. The area is then covered with top soil and seeded to blend with the natural terrain. Most of the older surface mines were not backfilled, nor are many of the currently active surface mines.

1.2.2 Underground Mining

Underground mining is much less disruptive to the surface terrain than open pit mining. In underground mining, access to the ore body is gained through one or more vertical shafts, generally sunk to a slightly greater depth than the ore body, or through inclines, declines, or adits, all cut through waste rock. Ore deposits are closely followed during mining to minimize the amount of waste material which must be brought to the surface. When mining in large deposits, other mining methods are used, for example, the room and pillar technique. This technique involves caving-in a large section of ore deposits. The ore is broken by drilling and blasting and then brought to the surface. The ore and waste is moved out of the mine through tunnels and shafts leading to the surface. The waste rock is removed to a spoils area that may be surrounded by a ditch to contain water runoff. The surface area affected by underground mining activities generally involves less than about 20 hectares, but the underground mine-works may extend laterally for more than a mile in several directions and at several depths. For example, an areal survey of 10 underground mining sites located in New Mexico (9) and Wyoming (1) indicated that the disturbed surface areas varied from 0.9 to 17 hectares, with an average of 12 hectares per site (EPA83).

1.2.3 Other Mining Methods

Other uranium mining methods include heap leaching, in situ mining, and mine water recirculation. These methods have become more common in recent years (EPA83, EIA88a). However, they are not anticipated to create a significant amount of overburden in comparison to the inventory of surface and underground mine waste. Both heap leaching and in-situ mining are performed by adding chemicals to leach the uranium from ore materials. The leachate is subsequently processed to recover the uranium. In 1978, nearly 7 percent of the total U_3O_8 production was associated with such mining methods (EPA83). The contribution from this sector has continually increased since 1978 and, on the average, about 20 percent of uranium ore production is currently due to these mining methods (EIA88a).

1.3 ORE AND WASTE PRODUCTION

At the onset of the uranium mining industry, most of the ore was recovered from deposits located at or near the surface. As easily accessible ore deposits became depleted, mining had to be performed at increasing depths. In addition, lower grade ore deposits, once ignored, were later mined by using improved mining methods and more efficient ore extraction techniques.

In the early mining years, an ore grade of 0.15 percent was typically ignored, while more recent mining practices target ore grades as low as 0.03 percent (EPA83). Accordingly, the mining industry has, over the years, been required to move larger quantities of topsoil and overburden in order to reach less accessible or lower grade ore deposits. The amount of overburden which must be removed to expose the uranium ore is also known to be significantly different for surface and underground mines.

Characteristics of uranium mine wastes vary with the geologic formation from which they are extracted. Only about 5 percent of domestic production is from vein-type deposits (generally in metamorphic or igneous rocks). The majority of the uranium ore has been mined in geologic formations which include sandstone, claystone, siltstone, shale, and limestone deposits. Other materials routinely or occasionally contained with ores or mining

wastes may include silt, gravel, sand, volcanic ash, and lignite. Mine wastes derived from sandstone deposits typically consist of various proportions of sand, silt, soil, and sandstone as rocks, cobbles, and boulders. Rock and waste materials vary in size from small particles to large boulder size rocks. Typically, such wastes are stored in areas which are unconsolidated and not reclaimed. The overburden or spoil areas have poor textural properties, do not support vegetative growth, and have very poor water-holding capacities. Since most of these sites are located in arid regions of the United States, spoil areas are usually barren.

1.3.1 Waste Volume Projections

Table B.1-3 presents yearly uranium ore production and estimated overburden generation rates for both surface mines and underground mines. The rationale for the bases used to estimate overburden generation rates is explained in the following paragraphs.

The ratio of overburden to ore produced in an open pit mine can vary from 10:1 to as high as 80:1 (EPA83). This ratio is thought to have been fairly constant (about 9 to 12) from 1948 to the late 1950s. From about 1960 to the early 1980s, the ratio has progressively increased from a low of about 15 to an estimated high of 77 for large surface mines. For example, over a three decade period, the ratio was about 20 during the 1960s, about 30 by 1970, and between 40 to 50 by the mid 1970s. The EPA, in its Report to Congress, assumes an average ratio of 50:1 since most of the sites are comprised of smaller mining facilities (EPA83). For this report, four waste to ore ratios are applied to the yearly ore production rates to estimate the generation of overburden wastes from surface mines. A ratio of 10:1 is assumed to characterize practices from 1948 to 1960, 25:1 from 1961 to 1970, 40:1 from 1971 to 1980, and 60:1 from 1981 to 1988. This approach is used to more correctly reflect practices over the past 40 years since applying a single ratio of 50:1 for all years would overestimate the amount of waste generated during the first three decades.

Underground mines are exploited in a way that minimizes the removal of waste rock, resulting in much smaller spoil storage piles than those at surface mines. As opposed to surface mines, the waste to ore ratio is often less than one for underground mines. It is estimated that the waste to ore ratio generally ranges from 1:20 to 1:1, with an average ratio

Table B.1-3. Estimated uranium mining overburden production.^a

Year	Surface Mines^b		Underground Mines^b	
	Ore (MT)	Overburden (MT)^c	Ore (MT)	Overburden (MT)^d
1948	<9.0E+2	9.0E+3	3.4E+4	1.1E+4
1949	9.1E+2	9.1E+3	1.6E+5	5.3E+4
1950	2.1E+4	2.1E+5	2.1E+5	7.0E+4
1951	2.5E+4	2.5E+5	2.9E+5	9.7E+4
1952	5.9E+4	5.9E+5	3.4E+5	1.1E+5
1953	1.6E+5	1.6E+6	5.0E+5	1.7E+5
1954	2.4E+5	2.4E+6	7.6E+5	2.5E+5
1955	3.4E+5	3.4E+6	1.0E+6	3.3E+5
1956	1.1E+6	1.1E+7	1.6E+6	5.3E+5
1957	1.5E+6	1.5E+7	1.9E+6	6.3E+5
1958	2.1E+6	2.1E+7	2.6E+6	8.7E+5
1959	2.0E+6	2.0E+7	4.3E+6	1.4E+6
1960	2.2E+6	2.2E+7	5.1E+6	1.7E+6
1961	2.3E+6	5.8E+7	5.0E+6	1.7E+6
1962	1.6E+6	4.0E+7	4.8E+6	1.6E+6
1963	1.7E+6	4.3E+7	3.7E+6	1.2E+6
1964	1.4E+6	3.5E+7	3.4E+6	1.1E+6
1965	1.1E+6	2.8E+7	2.8E+6	9.3E+5
1966	1.2E+6	3.0E+7	2.7E+6	9.0E+5
1967	1.4E+6	3.5E+7	3.4E+6	1.1E+6
1968	2.1E+6	5.3E+7	3.7E+6	1.2E+6
1969	2.0E+6	5.0E+7	3.4E+6	1.1E+6
1970	2.5E+6	6.3E+7	3.2E+6	1.1E+6
1971	3.0E+6	1.2E+8	2.7E+6	2.7E+6
1972	3.5E+6	1.4E+8	2.3E+6	2.3E+6
1973	4.1E+6	1.6E+8	1.8E+6	1.8E+6

Table B.1-3. Continued.

Year	Surface Mines^b		Underground Mines^b	
	Ore (MT)	Overburden (MT)^c	Ore (MT)	Overburden (MT)^d
1974	3.8E+6	1.5E+8	2.6E+6	2.6E+6
1975	3.9E+6	1.6E+8	2.5E+6	2.5E+6
1976	4.2E+6	1.7E+8	3.6E+6	3.6E+6
1977	5.1E+6	2.0E+8	4.3E+6	4.3E+6
1978	7.5E+6	3.0E+8	5.5E+6	5.5E+6
1979	8.8E+6	3.5E+8	4.9E+6	4.9E+6
1980	9.4E+6	3.8E+8	5.8E+6	5.8E+6
1981	7.7E+6	4.6E+8	4.7E+6	4.7E+6
1982	5.0E+6	3.0E+8	2.5E+6	2.5E+6
1983	3.4E+6	2.0E+8	4.3E+6	4.3E+6
1984	1.8E+6	1.1E+8	9.3E+5	9.3E+5
1985	8.5E+5	5.1E+7	5.2E+5	5.2E+5
1986	1.3E+5	7.8E+6	6.0E+5	6.0E+5
1987	7.4E+5	4.4E+7	5.6E+5	5.6E+5
1988	6.3E+5	3.8E+7	4.7E+5	4.7E+5
40-yr period 1949-1988:		3.9E+9		6.9E+7
20-yr period 1969-1988:		3.5E+9		5.3E+7
10-yr period 1979-1988:		2.0E+9		2.5E+7

a Data extracted from Uranium Industry Annual - 1988 (EIA88a).

b Quantities are expressed in metric tons (MT), e.g., 1.1E+6 means 1,000,000 metric tons.

c Amount of overburden materials from surface mines is calculated by applying a waste to ore ratio of 10:1 from 1948 to 1960, 25:1 from 1961 to 1970, 40:1 from 1971 to 1980, and 60:1 from 1981 to 1988.

d Amount of overburden materials from underground mines is calculated by applying a waste to ore ratio of 1:3 from 1948 to 1970, and 1:1 from 1971 to 1988.

of about 1:9 (EPA83). As with surface mining, this ratio has also increased over the years from within a range 1:5 to 1:2.5 until the early 1970s to about 1:1 by the late 1970s. For the purpose of this report, the ratio of overburden to ore for underground mines is assumed to be 1:3 from 1948 to 1970 and 1:1 from 1971 to 1988. This approach is used to more correctly reflect practices over the past 40 years since applying a single ratio of 1:9 for all years would significantly underestimate the amount of waste generated during the last two decades.

Table B.1-3 shows that the total volume of uranium mine waste produced since the inception of the industry is about 4 billion metric tons. Most of this waste (almost 90 percent) has been produced by surface mining during the past 20 years. Wastes produced from surface uranium mines are substantially greater (by a factor of about 50) than the volume produced from underground mines; and, therefore, the production from surface mines is the determining factor in estimating the total NORM inventory. Of the more than 1,300 surface uranium mines identified in Table B.1-2, over 1,000 have had ore production of less than 900 MT. Mines of this size typically have few or no waste piles associated with past waste production. As a result, the NORM inventory is most predicated by the remaining 257 surface mines producing more than 900 MT (SCA89). Since the last 20 years includes the period of heaviest surface mining, future projections based on this time period would yield highly conservative estimates, unless there is a major upturn in the demand for uranium.

For example, assuming that the generation of overburden remains the same as that observed from 1985 to 1988, since ore production has reached a new plateau, the 20-year waste production is 700 million MT versus 3.5 billion MT, which is the total 20-year inventory from 1960 to 1988. Since most of the demand for uranium originates from the commercial sector (nuclear power plants), it is anticipated that, in view of the downturn in new plant construction, the future production rate of uranium will be one which matches existing needs for refueling rather than supporting the demand of new power plants (EIA88b, EIA88c). The domestic demand for uranium is also partially met by importing U_3O_8 from abroad (EIA88a). Since 1975, imports of uranium have continually increased from about 640 MT to 7,200 MT in 1988 (EIA88a). An increase in uranium imports would further reduce mining activity in the United States and consequently reduce the generation of overburden waste.

1.3.2 Reclaimed Versus Unreclaimed Material

The projected waste inventory and its potential to cause elevated exposures to the public must also take into consideration the fact that certain states have implemented regulatory controls requiring the submittal of a reclamation plan and bond prior to the issuance of a mining permit. The purpose of reclamation is to return the excavated areas to more aesthetic conditions and reduce the potential for surface water runoff and erosion. This generally consists of backfilling, regrading, and seeding the excavated areas. Though these programs are not explicitly designed to mitigate potential radiological risks, such measures do reduce potential exposures to direct radiation, radon, fugitive dust emissions, and the possibility that materials will be removed and used in construction applications.

Some mines which were subject to State regulations have been reclaimed, but the number of such mines still makes up a small fraction of the total. For example, the EPA estimated that by 1971 approximately 6 percent of the land used for uranium mining had been reclaimed. Mines operating prior to the implementation of regulations requiring reclamation (such as the Wyoming Environmental Quality Act of 1973 and the Texas Surface Mining Act of 1975) and mines located in states not implementing such controls are generally still unreclaimed today. The exceptions are Texas and Wyoming where alternative funds have been allocated for reclamation. Any future reclamation activities will most likely alter the existing and projected volumes of unreclaimed waste.

The reclamation status of mines within various mining districts differs greatly depending upon state regulations. Two primary reclamation techniques are used, Class I and Class II. Class I reclamation is defined as complete backfilling followed by the application of topsoil, contouring, and re-vegetation. It is assumed that following Class I reclamation, the potential for exposure of the public has virtually been eliminated and the site returned to its original or near original condition. Therefore, the post-reclamation impact from Class I reclamation is about the same as the impact before any mining took place. Class II reclamation may consist of regrading, contouring, sloping, application of topsoil and re-vegetation of waste piles and pit surfaces. Waste materials are not usually totally returned to mined-out areas.

Table B.1-4 presents estimates of the number of sites and mining regions which have been subjected to some form of reclamation based on a study conducted in support of the 1989 NESHAPS (SCA89, EPA89). Table B.1-4 takes into account the number of mines in each reclamation classification for three ore production ranges: less than 900 MT, from 900 to 90,000 MT, and greater than 90,000 MT. These uranium ore production ranges reflect a Department of Energy survey scheme to classify various mining facilities (EPA83). As can be noted from Table B.1-4, only a small fraction of mining facilities have been subjected to Class I reclamation.

1.3.3 Uranium Overburden Utilization

Most uranium mining has taken place in rural or desolate areas of the southwest and western regions of the United States. Most mines are located on private property or on government owned land. Overburden materials are typically stored on-site. Because of the large volumes involved, the materials are moved, if at all, only to short distances from the mining areas. Overburden wastes have been used on-site to construct roads and as road ballast. Because of the coarse and rough form of such materials, there is no known direct use of overburden wastes which involve large volumes (EPA83). It should be noted that there is a paucity of information and data characterizing past uses and applications of such waste.

Field investigations have identified locations of higher than normal radiation exposure rates in local and nearby mining communities (EPA83, CRC81, NCR87, DOE88). Typically, most of the materials observed or used in nearby communities are characterized as tailings, ore spillage, ore specimens, low-grade crushed ore, and mine wastes. Past experience has shown that by far the most prevalent misuse of any uranium wastes (in large quantities) has involved mill tailings (DOE88). It is unlikely that valuable ores would be used at off site locations; rather the use of mining materials would typically involve mining wastes or processed materials which have little value for ore production and which have desirable characteristics for construction applications.

Given the physical characteristics of uranium overburden wastes, it is unlikely that this material would be used in construction of residential or commercial structures. For

Table B.1-4. Surface uranium mining industry based on regional reclamation.^a

I. For production ranges of 900 to 90,000 metric tons.

<u>State</u>	<u>Production</u>	<u>Reclamation Distribution</u>		
		<u>Class I</u>	<u>Class II</u>	<u>Unreclaimed</u>
Arizona	37	0	2	35
California ^c	1	0	0	1
Colorado	12	0	2.4	9.6
Idaho ^c	1	0	0	1
Montana ^c	1	0	0	1
Nevada ^c	1	0	0	1
New Mexico	3	0	0.5	2.5
North Dakota	10	0	0.5	9.5
Oregon	1	0	0	1
South Dakota	33	0	1.7	31.3
Texas	19	1.9	8.6	8.5
Utah	6	0	0	6
Washington	3	0	1.5	1.5
Wyoming	<u>66</u>	<u>3.3</u>	<u>26.4</u>	<u>36.3</u>
Total	194	5.2	43.6	145.2

a Data derived from two reports characterizing radiological conditions at surface uranium mines (SCA89, EPA89).

b Many mines have been partially reclaimed, hence the data are presented in fractional form in some instances.

c Sites are assumed to be unreclaimed for the lack of better information.

Table B.1-4. Continued.

II. For production greater than 90,000 metric tons.

Number of Surface Uranium Mines^b				
State	Production	Reclamation Distribution		
		Class I	Class II	Unreclaimed
Arizona	1	0	0	1
California ^c	0	0	0	0
Colorado	4	0.2	0.8	3
Idaho ^c	0	0	0	0
Montana ^c	0	0	0	0
Nevada ^c	0	0	0	0
New Mexico	5	0	0.8	4.2
North Dakota	0	0	0	0
Oregon	1	0	0	1
South Dakota	2	0	0.1	1.9
Texas	25	2.5	11.3	11.2
Utah	0	0	0	0
Washington	2	0	1	1
Wyoming	<u>31</u>	<u>1.6</u>	<u>12.4</u>	<u>17.0</u>
Total	71	4.3	26.4	40.3

a Data derived from two reports characterizing radiological conditions at surface uranium mines (SCA89, EPA89).

b Many mines have been partially reclaimed, hence the data are presented in fractional form in some instances.

c Sites are assumed to be unreclaimed for the lack of better information.

example, overburden materials would need to first be sorted to remove large boulders and rocks and then crushed or pulverized to form a material which would be in a suitable form for construction applications, e.g., as an additive to concrete, bricks, concrete blocks, grouts, etc. Since other types of construction materials are readily available, typically at much lower costs, it is not likely that uranium overburden materials will displace other competing products. Given that it is unlikely that overburden wastes may be misused in the construction of residential or commercial structures, the other more likely type of exposure which may present some radiological risks involves land use, such as use of the land for grazing, agricultural croplands, and residential or commercial developments.

The use of former mining sites for grazing beef cattle or for agricultural croplands would necessitate that former sites first be reclaimed in order to support vegetative growth. As was noted earlier, overburden or spoil areas have poor textural properties, do not support vegetation, and have very poor water-holding capacities. For this type of land to become productive, even typical reclamation measures may not be adequate. Since most uranium mine sites are located in arid and barren regions of the United States, waste dump areas are devoid of a top soil layer with the necessary plant nutrients and sufficient water to support most forms of agricultural production. If typical reclamation measures were implemented, such sites might possibly become suitable as grazing ranges for beef cattle.

It is difficult to determine if former mining sites could be developed into residential or commercial property. Given that such sites are generally located in remote areas, it is unlikely that abandoned or reclaimed sites would become busy urban developments. Since some older mines are now being exploited, a more likely scenario is one in which temporary housing is built at the site to support the work force engaged in the mining effort. As was noted earlier, the productive life of these mines is relatively short, typically 3 to 6 years. In this scenario, only a small transient work force would remain at the mining site.

1.3.4 Twenty-Year Projection of Unreclaimed Waste

As was discussed above, the reclamation status of mines within various mining districts differs greatly depending upon state regulations. Two primary reclamation techniques are used, Class I and Class II. It is assumed that following Class I reclamation,

the potential for exposure of the public has been virtually eliminated and the site has been returned to its original or near original condition. Therefore, all sites which have been subjected to Class I reclamation are assumed to present no additional risks above the natural background environment. For Class II reclamation, the mine waste inventories are assumed to be 50 percent of completely reclaimed mines. Mines classified as totally unreclaimed are assumed to have all of the estimated waste inventory (100 percent) remaining at the site in an unstabilized form.

Based on Table B.1-4 estimates, the number of surface mines in each ore production range are used to calculate the quantities of remaining overburden wastes for each reclamation classification. The amount of ore generated is estimated on the basis of the number of sites which have been subjected to reclamation, the total ore production for each of the three categories of mines, and total ore production from 1948 to 1988. In addition, it is assumed that the waste to ore ratio varies as a function of the size of the mine. Based on the EPA Report to Congress, the following waste to ore ratios are applied: 10:1 for small mines which produce less than 900 MT, 30:1 for mid-size mines which produce between 900 to 90,000 MT, and 50:1 for large mines which produce more than 90,000 MT of ore (EPA83). From a total of 1,305 mines, it is assumed that 1,040 mines have an average production of 300 MT each, or 1/3 of the range assuming a rough geometric distribution. For 194 mines which produce between 900 and 90,000 MT, the ore production is assumed to be 30,000 MT, also based on 1/3 of the range. For the remaining 71 larger mines, the ore production is assumed to be 1.1 million MT based on an EPA characterization of larger facilities (EPA83).

The largest mines are assumed to have a yearly ore production rate ranging from about 70,000 to 140,000 MT given that the productive life of a mine typically varies from 8 to 15 years (EPA83). For the sake of comparison, the EPA in its Report to Congress assumes that the average mine generates 120,000 MT of ore per year. The estimated total unreclaimed overburden, generated over the period of 1948 to 1988 is 3.1 billion MT. It should be noted that this amount represents nearly 80 percent of the total overburden waste generated since 1948 and about 89 percent of the amount produced from 1968 to 1988. The breakdown by reclamation Class is as follows:

<u>Mine Category</u>	<u>Unreclaimed Overburden (MT)^(a)</u>			
	<u>Class 1</u>	<u>Class II</u>	<u>Unreclaimed</u>	<u>Total</u>
Less than 900 MT	0	0	3.1E+6	3.1E+6
From 900 to 90,000 MT	0	2.0E+7	1.3E+8	1.5E+8
Greater than 90,000 MT	0	7.3E+8	2.2E+9	2.9E+9
Total	<u>0</u>	<u>7.5E+8</u>	<u>2.3E+9</u>	<u>3.1E+9</u>

(a) 3.1E+6 means 3,100,000 MT.

Given the uncertain status of the uranium mining industry, it is difficult to predict future generation rates. As can be seen from Table B.1-2, the uranium mining industry has taken a downturn since the early 1980s. The current ore production rate (for 1988) is typically less than 10 percent of the productive capacity experienced during the mid-1970s. Production is also shifting away from surface mines to underground mines, since the gradual depletion of surface mines requires that uranium be mined at increasing depths. Underground mining is also taking place at older or abandoned mines since it is too costly to develop new mines. Mining methods are also being more selective by targeting smaller but richer ore deposits or veins (PIE89). By today's standards, significant amounts of uranium still remain in these older mines. In the early mining years, an ore grade of 0.15 percent was typically ignored, while current mining practices target ore grades as low as 0.03 percent (EPA83).

Uranium can also be supplied from other sources since U_3O_8 may be extracted, as a by-product material, from other mineral mining activities, e.g., from phosphoric acid production, and extraction from copper mine wastes. Such alternate sources have supplied relatively small quantities, e.g., less than 1,000 MT in 1978 and current trends indicate that the number of such sources has continually decreased every year since 1981 (DOE88).

The productive life span of a uranium mine is also becoming much shorter. The EPA, in its 1983 Report to Congress, assumed that the typical life of a mine was about 8 to 15 years (EPA83). A review of current mining practices, however, reveals that the typical mine

is operational for only 3 to 6 years (PIE89, EPA89). Furthermore, it is anticipated that, at least in the foreseeable future, there will not be a growth in the nuclear power industry which would parallel the demand for uranium noted during the 1970s. Finally, there is the possibility that uranium imports may increase to still higher levels (EIA88a).

It is also safe to assume, given the more restrictive regulatory climate of the 1980s compared to the 1960s and 1970s, that even if the nuclear industry were to rebound, mining practices and reclamation activities will be conducted under more stringent regulations. New regulations would likely result in the generation of smaller quantities of overburden and institute some mandatory levels of reclamation on all new mining sites.

Accordingly, for this NORM sector the potential problem associated with the storage or use of overburden materials at uranium mine sites does not necessarily depend upon future activities, but rather on activities at existing sites. These sites include those that are still active and those that have yet to be reclaimed.

1.4 RADIOLOGICAL PROPERTIES OF URANIUM MINE WASTE

1.4.1 Radionuclide Concentrations

The concentration of naturally-occurring radioactivity in mining wastes is known to vary significantly (EPA85, NRC80, UNS82). In an EPA study of 58 samples taken from uranium mines it was noted that 69 percent had radium concentrations greater than or equal to 5.0 pCi/g, and 50 percent had concentrations greater or equal to 20 pCi/g. In a separate study, the EPA estimated that waste rock from uranium mining has average U-238 and Th-232 concentrations of 6.0 and 1.0 pCi/g, respectively (EPA83).

The results of recent field studies indicate that the average Ra-226 concentration in mine overburden is about 23.7 pCi/g, based on area weighted sample results in five states (SCA89). The range of Ra-226 concentration was noted to vary from about 3 pCi/g to several hundred pCi/g at the interface of overburden and low- grade ore boundaries. Background

Ra-226 concentrations are usually lower, typically ranging from about 1 to 7 pCi/g. The radium concentrations are estimated to be in equilibrium with parent members of the U-238 decay series, including U-238, U-234, and Th-230. For this report, it is assumed that the Ra-226 concentration in mining overburden is 23.7 pCi/g based on the above discussion and field data. The estimated radionuclide concentrations are as follows:

<u>Radionuclide</u>	<u>Concentration (pCi/g)</u>
Po-210	16.6
Pb-210	16.6
Ra-226	23.7
Th-228	1.0
Ra-228	1.0
Th-230	23.7
Th-232	1.0
U-234	23.7
U-235	1.2
U-238	23.7

Po-210 and Pb-210 concentrations are derived by applying a radon emanation coefficient of 0.3, assuming that the radionuclides are contained in a sandstone matrix (NRC84). The U-235 concentration is assumed to be 5 percent that of the U-238. Thorium and its decay chain members, Th-232, Ra-228, and Th-228, are assumed to be in secular equilibrium at a background concentration of about 1.0 pCi/g.

1.4.2 Radon Flux Rates

The concentration of long-lived radon daughters in the waste is based on the Ra-226 concentration and consideration of losses due to radon emanation and diffusion from the pile (NRC82). Field data (SCA89) indicate a large variation in radon emanation coefficients, ranging from approximately 0.1 to 0.5. Field measurements also indicate that average radon flux rates vary from about 2 to 60 pCi/m²-s for overburden materials and as high as few hundred pCi/m²-s for low grade ore materials (SCA89, EPA89). The flux rate averaged over 25 mines was estimated to be 11.1 pCi/m²-s for overburden materials. The large range of radon flux values is due to the wide range of radium concentrations found in overburden and

low grade ore materials. For comparison, background radon flux rates are known to vary from about 0.6 to 5.0 pCi/m²-s (SCA89, NRC80).

As was discussed earlier, it is difficult to characterize radon emanation or flux rates from such materials because of their diverse physical form and emplacement disposal or storage methods. For example, particle grain size and the presence and thickness of a cover will govern the radon emanation rates.

For this report, a simple approach is used to estimate the radon release rates from overburden piles. A radon emanation coefficient of 0.3 is used, based on the assumption that mining is occurring in sandstone formations (NRC84). Since the amount of overburden far exceeds the volume of low grade ore materials, it is assumed that any radon emanation from low-grade ore materials will most likely have little additional impact on the average emanation rate associated with the overburden waste alone.

1.4.3 External Radiation Exposure Rates

In support of the characterization of 25 uranium mine sites located in five states, external radiation measurements were taken on overburden piles (SCA89, EPA89). The field measurements revealed that exposure rates from overburden materials, on the average, varied from 20 to 110 μ R/hr, with a mean of about 40 μ R/hr. Exposure rates from low-grade ore materials were usually higher, ranging from 80 to nearly 1,000 μ R/hr, with an average of 200 μ R/hr. Exposure rates associated with ambient background levels were noted to range from 10 to 85 μ R/hr, averaging about 20 μ R/hr.

1.5 GENERIC SITE PARAMETERS AND SECTOR SUMMARY

1.5.1 Generic Overburden Site

The reference location for a surface uranium mine is south central Texas. This area was chosen due to a localized concentration of larger surface mines, more extensive land use, and relatively higher population density compared to sites in Colorado, South Dakota, New Mexico, and Wyoming. The reference site is assumed to be an unreclaimed and abandoned surface mine. Total ore production from the mine is estimated to be 1,100,000 MT, which is similar to large mine production in Wyoming, Colorado, and Texas (SCA89). The waste inventory is calculated using the 50:1 waste to ore ratio applied to large surface uranium mines, yielding a total waste volume of 55 million metric tons.

As previously mentioned, the generic site contains an uncovered and unreclaimed overburden pile with an associated mine pit. The effective volume of the waste pile is 28 million m³, assuming a density of 2.0 g/cm³. The pile is assumed to be approximately square, each side having a length of 1,200 m, and to have a height of 20 m.

1.5.2 Population Exposure

Population distributions around former mining sites are believed to have either remained constant or possibly decreased because of the downturn of the uranium industry since the beginning of this decade. The EPA, in its 1983 Report to Congress, characterized the population density around mining sites in 121 counties located in 17 states based on 1975 population estimates (EPA83). Based on the results of the 1980 census and 1986 update, the population in these states has increased, on the average, by about 45 percent since 1975 (BOC87). Population densities, adjusted for the 1986 population estimates, are reported to average 6.4 persons per km² (1 square mile is equal to 2.6 square kilometer) based on a total population of 9.6 million and a land area of 1.5 million square kilometers. With the exception of 22 counties, all remaining 99 counties were characterized by population densities of less than 10 persons per km². In the 22 most populous counties, population densities varied from 10 to 174 persons per km², with an average of 41 persons per km².

For the purpose of this assessment, a population density of 64 persons per square mile is assumed, based on Texas population data (BOC87).

1.5.3 Radionuclide Concentrations

As noted previously, the concentration of naturally-occurring radioactivity in mining wastes is known to vary significantly. For this risk assessment, radionuclide concentrations are based on the results of field studies and published data in the open literature. Radium concentrations are estimated to be in equilibrium with parent members of the U-238 decay series, including U-238, U-234, and Th-230. Po-210 and Pb-210 concentrations are derived by applying a radon emanation coefficient of 0.3. The U-235 concentration is assumed to be 5 percent that of U-238. Thorium (Th-232) decay chain members, Ra-228, and Th-228, are assumed to be in secular equilibrium at a background concentration of about 1.0 pCi/g. The reference radionuclide concentrations used in the uranium overburden risk assessment of Chapter D are given in Section 1.4.1.

B.1 REFERENCES

- BOC87** Department of Commerce, Statistical Abstract of the United States - 1988, Bureau of Census, 108th Edition, December 1987.
- CRC81** Conference of Radiation Control Program Directors, Natural Radioactivity Contamination Problems, Report No. 2, August 1981.
- DOE88** Department of Energy, Integrated Data Base for 1988: Spent Fuel and Radioactive Waste Inventories, Projections, and Characteristics, DOE/RW-0006, Rev.4, September 1988.
- EIA88a** Energy Information Agency, Uranium Industry Annual-1988, Department of Energy, DOE/EIA-0478(88), August 1989.
- EIA88b** Energy Information Agency, Annual Outlook for U.S. Electric Power - 1988, Department of Energy, DOE/EIA-0474(88), August 1988.
- EIA88c** Energy Information Agency, Commercial Nuclear Power - 1988, Department of Energy, DOE/EIA-0438(88), September 1988.
- EPA83** Environmental Protection Agency, Potential Health and Environmental Concerns of Uranium Mines Wastes, Report to the Congress, EPA 520/1-83-007, June 1983.
- EPA85** Environmental Protection Agency, Wastes from the Extraction and Beneficiation of Metallic Ores, Phosphate Rock, Asbestos, Overburden from Uranium Mining, Report to Congress, EPA 530/SW-85-033, December 1985.
- EPA89** Environmental Protection Agency, Background Information Document Proposed NESHAPS for Radionuclides, Draft, SC&A, Inc. report prepared for the U.S. EPA 520/1-89-006, February 1989.
- NCR87** National Council on Radiation Protection and Measurements, Exposure of the Population in the United States and Canada from Natural Background Radiation, NCRP Report No. 94, December 1987.
- NRC80** Nuclear Regulatory Commission, Final Generic Environmental Impact Statement on Uranium Milling, NUREG-0706, Vol. III, September 1980.
- NRC82** Nuclear Regulatory Commission, Radon and Aerosol Release from Open Pit Uranium Mining, Pacific Northwest Laboratory Report PNL-4071, prepared for the U.S. NRC, NUREG/CR-2407, August 1982.
- NRC84** Nuclear Regulatory Commission, Radon Attenuation Handbook for Uranium Mill Tailings Cover Design, NUREG/CR-3533, April 1984.

- PIE89** **Pierce, P.E., Senior Mining Engineer, telephone communication, September 18, 1989.**
- SCA89** **Radiological Monitoring at Inactive Surface Uranium Mines, Roy F. Weston, Inc., report prepared for SC&A, Inc. under EPA contract, February 1989.**
- UNS82** **United Nations Scientific Committee on the Effects of Atomic Radiation, Ionizing Radiation: Sources and Biological Effects, No. E.82.IX.8, United Nations, 1982.**

B.2 PHOSPHATE AND ELEMENTAL PHOSPHOROUS WASTES

2.1 INTRODUCTION

Mining of phosphate rock (phosphorite) is the fifth largest mining industry in the United States in terms of quantity of material mined (EPA84). The southeastern U.S. is the center of the domestic phosphate rock industry, with Florida, North Carolina, and Tennessee having over 90 percent of the domestic rock production capacity. Florida, with approximately 80 percent of the current domestic capacity, dominates the U.S. industry and is the world's largest phosphate rock producing area. The western U.S. phosphate rock industry is located in eastern Idaho, northern Utah, western Wyoming, and southern Montana.

The principal ingredient of phosphate rock (or phosphorite) that is of economic interest is an amorphous form of the mineral apatite (francolite or carbonate-fluorapatite). Phosphate rock is processed to produce phosphoric acid and elemental phosphorous. These two products are then combined with other chemicals to produce phosphate fertilizers, detergents, animal feeds, other food products, and phosphorous-containing chemicals. The most important use of phosphate rock is the production of fertilizers, which accounts for about 80 percent of the mining of phosphorite in the United States.

Uranium in phosphate ores found in the U.S. ranges in concentration from 20 to 300 ppm (or about 7 to 100 pCi/g) (DEV79), while thorium occurs at lower concentrations, between 1 to 5 ppm (or about 0.1 to 0.6 pCi/g) (BLI88). Phosphogypsum is the principal waste byproduct generated during the phosphoric acid production process. Phosphate slag is the principal waste byproduct generated from the production of elemental phosphorous. Some of the impurities contained in the phosphogypsum and phosphate slag include uranium and thorium and their radioactive decay products, which are known to exist at elevated concentrations. Since large quantities of phosphate industry wastes are produced, there is a concern that these waste materials may present a potential radiological risk to exposed individuals if the wastes become distributed in the environment.

In the sections which follow, a description of the phosphate industry is provided along with a characterization of the properties of phosphate products and wastes. Actual and projected amounts of waste materials produced by this NORM sector are also given based on past and current industry practices.

This information is used to assess potential exposures to members of the general public and critical population group. A radiological risk assessment is performed (see Chapter D) assuming that the exposed population is residing near a generic facility.

2.2 OVERVIEW OF PHOSPHATE INDUSTRY

The 1988 U.S. production of phosphate rock has been estimated to be 38 million metric tons (MT), while the industry has a productive capacity of 50 million MT (TFI89). U.S. production peaked in 1980 when it produced 54 million MT (TVA86). Production has since been decreasing at about 2 percent per year (TVA86, BOM88, TFI89). Phosphate rock inventories have similarly decreased, from 15 to 7.5 million MT in 1985 and 1988, respectively (TFI89). The industry's total productive capacity is also following a similar trend. Phosphate rock is mined in open-pit mines, half of which are located in Florida, with the remaining half scattered in Tennessee, Idaho, Montana, Wyoming, Utah, and North Carolina, see Figure B.2-1.

Phosphate ore consists of one-third quartz sand, one-third various clay minerals, and one third phosphate particles. After mining the phosphate rock, the ore is processed by beneficiation (washing and flotation processes), followed by drying of the marketable rock. A flow chart of various phosphate production operations is shown in Figure B.2-2. After beneficiation, the marketable phosphate rock is transformed into either elemental phosphorous (thermal process), or phosphoric acid (wet-process) for the production of fertilizer, detergents, animal feeds, food products, and phosphorous-containing chemicals. About ten percent of the marketable phosphate rock mined in the United States is used for the production of elemental phosphorus. Regardless of the processing method, most of the phosphate rock production goes into the making of fertilizers, which accounts for about 80 percent of the production of phosphorite in the United States.

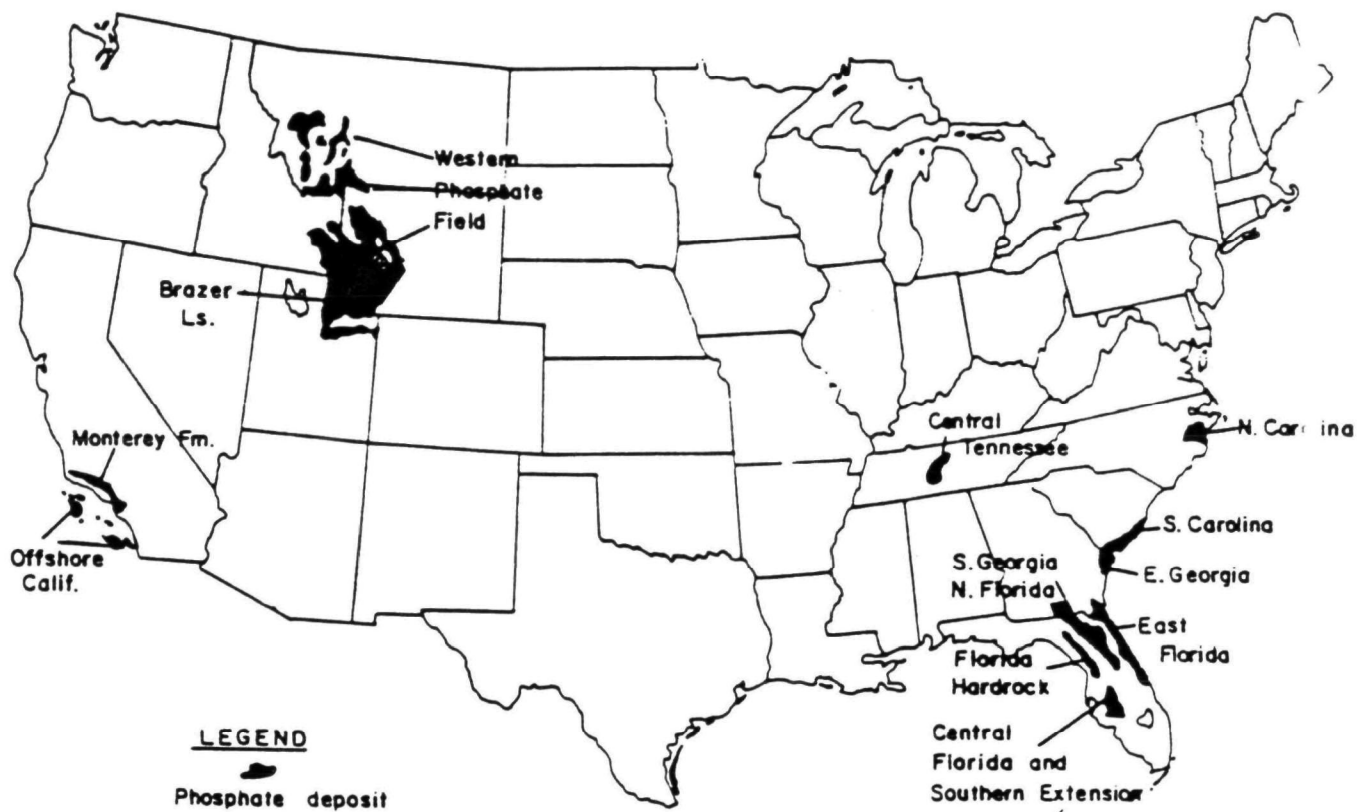


Figure B.2-1. Major uraniferous phosphate deposits in the U.S.

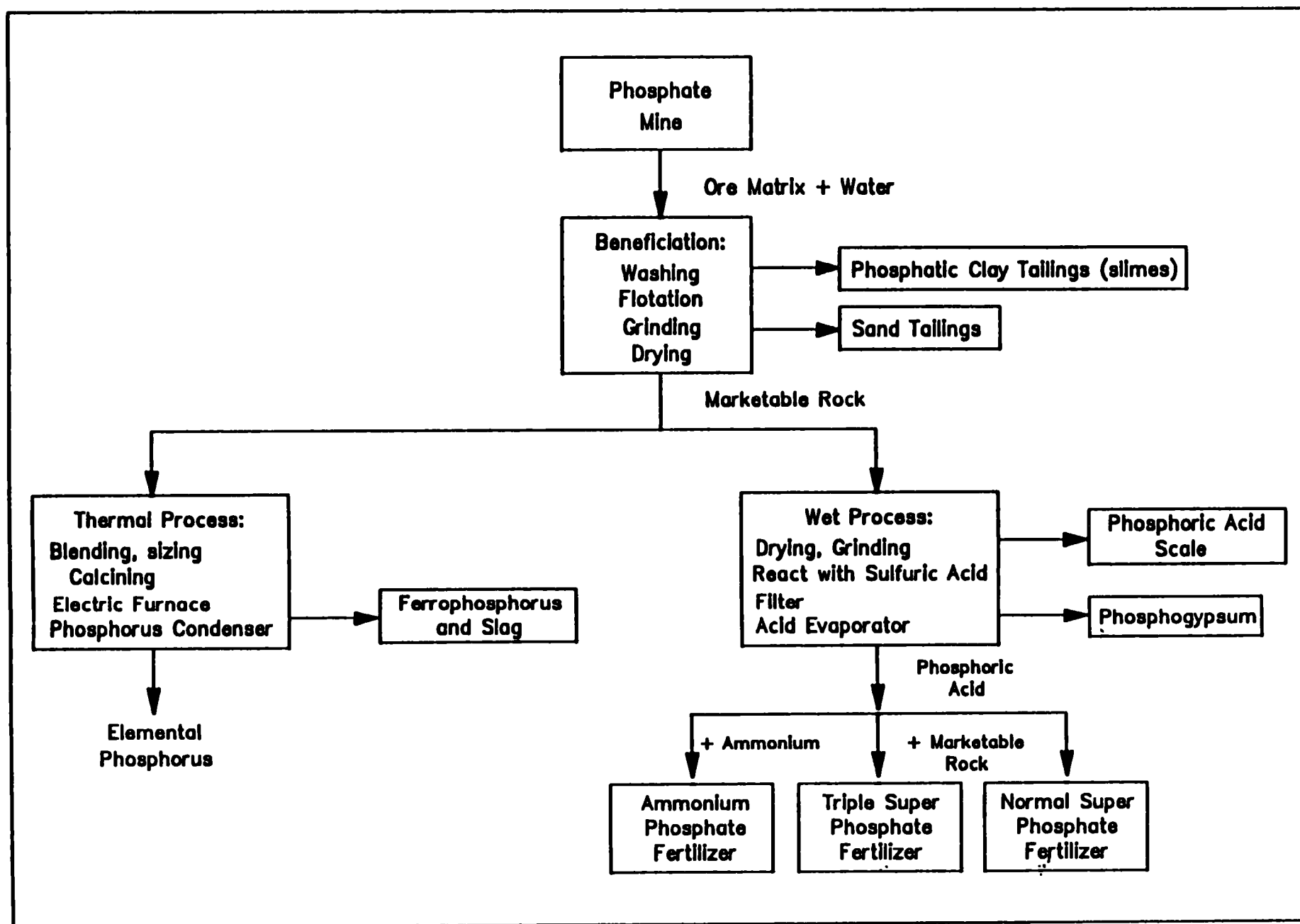


Figure B.2-2. Flow diagram of phosphate material and waste production.

2.2.1 Phosphoric Acid - Wet-Process

The phosphoric acid production industry in the U.S. consists of 21 facilities that were active and two that were on standby status as of September 1989 (EPA90a). The locations of these facilities are shown in Table B.2-1. The average wet-process plant produces about 700 metric tons of phosphoric acid per day (EPA88).

Production

The starting material for the production of phosphoric acid by the wet process is beneficiated phosphate ore. During beneficiation, phosphate particles are separated from the rest of the ore, and thus, two types of wastes are produced: 1) phosphatic clay tailings (clay slime from washer stages of beneficiation), and 2) sand tailings from flotation stages of beneficiation.

Phosphatic clay tailings (slime) are stored in large settling areas behind earthen dams. Clear water reclaimed from these settling areas is returned to the mine, providing a source of water for the wet-process or for use as process water in other parts of the plant.

Sand tailings are either returned to the mine and used as a backfill in mined-out areas (as is the practice in Florida and North Carolina), used for construction of clay-tailings retention dams (as is also the practice in Florida), or mixed with clay tailings to increase clay tailings solids content.

For each 13.3 million MT of phosphorite beneficiated in a typical central Florida mining operation, 3.3 million MT of phosphatic clay tailings, 7.3 million MT of sand tailings, and 2.7 million MT of marketable ore are produced annually. About one-half of the mined-out area is used to store phosphatic clay tailings in retention areas. When introduced into retention areas, the waste and clay slurry has a solid content of only three to six percent by weight. Accordingly, the volume of slurried waste clay far exceeds the volume of sand, phosphate, and clay originally removed from the mined area.

Table B.2-1. Wet process phosphoric acid plants (Source: EPA90b).

Operator	Location	Parent Company
Agrico	Donaldsonville, LA	Freeport-McMoRan
Agrico	Mulberry (Pierce), FL	Freeport-McMoRan
Agrico	Uncle Sam, LA	Freeport-McMoRan
Arcadian	Geismar, LA	Arcadian
Central Phos.	Plant City, FL	CF Industries
CF Chemicals	Bartow (Bonnie), FL	CF Industries
Chevron Chemical	Rock Springs, WY	Chevron, Corp.
Conserv	Nichols, FL	Conserv
Farmland Inc.	Bartow (Pierce), FL	Farmland Ind.
Fort Mead Chemical	Fort Meade, FL	US Agric Chem/WR Grace
Gardinier	Riverview (Tampa), FL	Gardinier
IMC Fertilizer	New Wales (Mulberry), FL	IMC Fertilizer
Mobil Mining	Pasadena, TX	Mobil Corp.
Nu-South Ind.	Pascagoula, MS	Nu-West Industries
Nu-West	Soda Springs, ID	Nu-West Industries
Occidental Chem.	White Springs, FL	Occidental Petroleum
Royster	Mulberry, FL	Cedar Holding Co.
Royster	Palmetto (Piney Pt), FL	Cedar Holding Co.
Seminole Fert.	Bartow, FL	Seminole Fertilizer
J.R. Simplot	Pocatello, ID	J.R. Simplot
Texasgulf	Aurora, NC	Texasgulf
 Agrico ^(a)	 Ft. Madison, LA	 Freeport - McMoRan
Agrico ^(a)	Hahnville, LA	Freeport-McMoRan

(a) On standby in 1989.

About 36 million MT (dry weight) of waste clay are produced annually in Florida alone. For each ton of clay solids produced, four to five tons of interstitial water remains permanently entrapped. More than 20,000 hectares (50,000 acres) of clay tailings settling areas surrounded by more than 300 miles of earthen dams (up to 12 m high) are now in existence in Florida (TWN88). The low bearing strengths of reclaimed clay slime retention areas, even after several decades of settling, limits their use only to agricultural applications.

After beneficiation, the marketable phosphate ore is sold to wet-phosphoric acid plants. Sulfuric acid is used to dissolve the ore; this reaction produces mostly hydrated calcium sulfate ($\text{CaSO}_4 \cdot n\text{H}_2\text{O}$, i.e., phosphogypsum, which is a waste by-product) and phosphoric acid (H_3PO_4), and smaller amounts of hydrofluoric acid (DEV79). The hydrofluoric acid is eventually turned into fluorosilicic acid, which can become a by-product of fertilizer production.

Digestion of the phosphate ore by sulfuric acid produces a slurry (phosphogypsum) which is further processed by filtration. The phosphogypsum is discharged from filter pans, slurried with water, and pumped to large piles (phosphogypsum stacks). The conditions of both the phosphate ore and the digester influence the filtration properties of the slurry. Phosphogypsum typically consists of thick and agglomerated crystals in order to achieve a good filtration rate and to maximize the production of phosphorus oxide (P_2O_5). Typical phosphogypsum particles range in size between 50-100 microns. Most of the sand impurities fall within this particle size range while the remaining impurities are comprised of particles which are less than 30 microns in size (CHA87). The final moisture content of phosphogypsum stacks stabilizes between 20 and 30 percent. Approximately 93 percent of the waste material is phosphogypsum, with the balance consisting of impurities which include sand, phosphate, fluorides, radionuclides, and organic constituents. Some of the radium from the original ore remains and co-precipitates with the calcium sulphate or phosphogypsum, while the balance, remains with the impurities. As is discussed in Section 2.4, the typical radium-226 concentration in phosphogypsum ranges from 11 to about 33 pCi/g (EPA75). For each ton of wet-process phosphoric acid, about 4.5 metric tons of phosphogypsum is produced. As is discussed later in this section, phosphogypsum is generated in large quantities.

An additional waste product of radiological concern that is associated with this process is phosphoric acid scale. In the production of phosphoric acid from the raw ore, the phosphogypsum must be physically separated from the phosphoric acid by a filtration process. Large stainless steel filter pans are covered with fiberglass fabric which serves to filter out the phosphogypsum while allowing the passage of acid. During this process, small quantities of scale are deposited on the surface areas of the pan and fiberglass mat. This scale can also be found deposited in ancillary piping and filtrate receiver tanks that are associated with the filtration process. Radium-226 concentrations in scales have been found to range from several hundred to as high as 100,000 pCi/g (KEA88). While the concentrations of radium-226 are quite high, the volume associated with this scale is relatively low. One estimate is that a phosphoric acid production plant will generate about 6 m³ of scale per year (MAR88). Some scale is also deposited within phosphogypsum stacks, either in the concentrated form, or mixed and diluted with lower concentration phosphogypsum. Because of the very low volume of this scale compared to the volume of phosphogypsum, phosphoric acid scale will not be treated further in this report.

2.2.2 Elemental Phosphorous - Thermal Process

Elemental phosphorus is used primarily for the production of high grade phosphoric acid, phosphate-based detergents, and organic chemicals used in cleaners, foods, baking powder, dentifrices, animal feed, etc. About 70 to 80 percent of the elemental phosphorous production is used to make phosphoric acid, while the balance is used elsewhere, e.g., for the making of pesticides and other high grade chemicals (TVA86). There are eight elemental phosphorus plants in the United States, located in Florida, Idaho, Montana, and Tennessee. Only five of these plants (in Idaho, Montana, and Tennessee) are presently active. Location, ownership, estimated capacity, and current status of the plants are shown in Table B.2-2 (EPA84, EPA90a). Production of elemental phosphorus has declined from a peak of 400 thousand MT in 1979 to 310 thousand MT in 1988 (REL89, EPA89a, DOI87, EPA90a). Between 1978 and 1988, U.S phosphorous production has declined at an effective annual rate of 2 percent (REL89). In 1986, approximately 20,000 MT of elemental phosphorus were exported and 4,000 MT were imported. In recent years, most American phosphorous producers have adjusted to the detergent phosphate bans and rising energy costs. Many

Table B.2-2. Location and capacity of elemental phosphorus plants.

Location	Company	Phosphorous Capacity^(a) (MT/yr)
Florida		
Pierce ^(b)	Mobil Chemical Co.	20,000
Tarpon Springs	Stauffer Chemical Co.	23,000
North Carolina		
Lee Creek ^(c)	Texas Gulf/Olin	48,000
Idaho		
Pocatello	FMC Corporation	130,000
Soda Springs	Monsanto Chemical Co.	90,000
Montana		
Silver Bow	Stauffer Chemical Co.	40,000
Tennessee		
Columbia	Occidental Chemical Co.	57,000
Columbia ^(b)	Monsanto Chemical Co.	75,000
Mt. Pleasant	Stauffer Chemical Co.	50,000

(a) Estimated capacity in 1984 (EPA84).

(b) These facilities are currently inactive.

(c) Wet-process under construction and scheduled for operation in early 1990 (REL89).

inefficient plants were shutdown and the productive capacity was concentrated in areas where energy supplies were the most cost effective.

Phosphorous is produced by the reduction of phosphate rock in large electric furnaces using carbon and silica as catalysts. The industry favors the use of thermal units rather than wet-process plants because the former produce phosphorous of a higher grade. Wet-process plants may require additional processing to produce phosphorous of similar purity. Thermal units, however, consume large amount of electricity and are preferably located where energy is the least costly. Crushed and screened phosphate rock is fed into calciners and heated to the melting point, about 1300°C. After calcining, the hot nodules are passed through coolers and into storage bins prior to being fed into electric furnaces. The furnace feed consists of nodules, silica, and coke. A simplified chemical reaction equation for the electric furnace process is:



Phosphorus and carbon monoxide, driven off as gases, are vented at the top of the furnace. Furnace off-gases pass through dust collectors and then through water spray condensers where the phosphorus is cooled to a molten state. The mix of phosphorus and water (phossey water) and mud is then processed to recover the phosphorus. During this process, another waste product, called slag, is generated. Typically, 90 percent of the phosphate rock which goes into making elemental phosphorous comes out of the process as waste (EPA85a). There are large inventories of slag stored at both currently operating and closed elemental phosphorus plants. This inventory has been estimated to be on the order of 200 to 400 million MT from production activities up to 1975 (CRC81).

The ferrophosphorus and CaSiO_3 slag are the principal NORM waste products from the production of elemental phosphorus, with mass balances showing that most radionuclides are being carried through the process. Because of furnace processing, slag is a glassy-like material containing the radionuclides in a vitrified matrix. Because of this physical property, slag waste is believed to be less susceptible to the leaching of radionuclides. In addition, the slag has a high carbonate content which also reduces radionuclide solubility (EPA85a). However, the EPA's Report to Congress on Special Wastes (EPA90a) documents groundwater contamination at several phosphate slag waste management sites. As discussed in Section

2.4, concentrations of uranium, thorium, and radium in elemental phosphorus slag have been measured as high as 50 pCi/g. However, because of the high temperatures involved, some radionuclides are vaporized. For example, as much as 95 percent of the lead-210 and polonium-210 has been observed in calciner stack releases (EPA81a, EPA81b, EPA84) and subject to NESHAPS (EPA89b).

2.3 PHOSPHOGYPSUM STACKS AND ELEMENTAL PHOSPHOROUS WASTES

2.3.1 Volume of Waste Materials

Phosphogypsum and elemental phosphorus slag are the phosphate wastes of primary interest in this NORM sector. Phosphate fertilizers are treated as a separate NORM sector (see Section B.3) since they are not waste products, do contain elevated levels of naturally-occurring radioactivity, and are widely applied over agricultural croplands.

Phosphogypsum (calcium sulfate) is the principal waste product from wet-process phosphoric acid production. The phosphogypsum is transferred as a slurry to disposal areas. These disposal areas, which are referred to as phosphogypsum stacks, are generally constructed directly on virgin or mined-out land with little or no prior preparation of the land surface (EPA88). Each phosphoric acid production facility may have one or more phosphogypsum stacks. Phosphogypsum stacks range in size from 2 to 300 hectares (750 acres) and range in height from 3 to about 60 meters. In addition to their large sizes, phosphogypsum stacks are characterized with other physical features. Large areas of the stack are typically covered with water in ponds, beaches, and ditches. Such surface features may cover large areas, up to 60 percent of the top section of the stack. Other surface features include areas with loose or crumbling materials, access roads, thickly-crusting top areas, and thinly-crusting stack sides.

A total of 63 stacks have been identified nationwide (EPA89a). Since most of the U.S. phosphate ore production takes place in Florida, this state has the largest number of stacks. The distribution of phosphogypsum stacks and their numbers are given in Table B.2-3. As

Table B.2-3. Location and number of phosphogypsum stacks.

State	Number of Stacks	Total Base Area and Number of Stacks ^(a)		
		Operating	Idle	Inactive
Arkansas	1	0	0	9 (1)
Florida	20	1,343 (16)	146 (1)	81 (3)
Idaho	6	117 (2)	17 (1)	27 (3)
Illinois	8	40 (1)	117 (2)	71 (5)
Iowa	3	0	0	64 (3)
Louisiana	7	505 (4)	63 (3)	0
Mississippi	1	101 (1)	0	0
Missouri	3	0	0	48 (3)
North Carolina	5	51 (1)	148 (4)	0
Texas	7	61 (1)	30 (3)	71 (3)
Utah	1	0	0	121 (1)
Wyoming	1	182 (1)	0	0
Total	63	2,400 (27)	521 (14)	492 (22)
Average Stack Area:	--	89 ha.	37 ha.	22 ha.

(a) Total base area is given first, in hectare (ha.), followed by the number of stacks shown in parentheses (EPA89a).

can be seen, the average stack base area is largest for operating stacks, being nearly 90 hectares. The average idle or inactive stack is smaller in size, 37 and 22 hectare, respectively. The average height is approximately 20 meters (EPA89a).

The production of phosphogypsum is estimated by applying the rule of thumb of 4.5 MT of phosphogypsum per MT of P_2O_5 (GUI75). For illustrative purposes, the yearly phosphate rock, phosphoric acid, and phosphogypsum production rates (TFI89, TVA86) are tabulated below for selected years since 1965.

<u>Year</u>	<u>Phosphate Rock</u> <u>(million MT)</u>	<u>Phosphoric Acid</u> <u>(million MT)</u>	<u>Phosphogypsum</u> <u>(million MT)</u>
1965	26.8	3.5	15.8
1970	35.1	5.2	23.4
1975	44.3	7.0	31.5
1980	54.4	9.8	44.1
1984	49.2	9.9	44.6
1985	44.8	8.9	40.1
1986	32.8	7.4	33.3
1987	35.7	8.1	36.5
1988	38.3	9.3	41.9

These years were selected because they capture the productive capacity of the phosphate mining industry for the last 20 years. As can be seen, the yearly phosphogypsum production has averaged nearly 40 million MT since 1984. The total phosphate waste volume generated in the U.S. from 1910 to 1981 has been estimated at 7.7 billion metric tons (EPA85a). In Central Florida, the phosphoric acid industry produces about 32 million MT of phosphogypsum each year, with a current stockpile of nearly 400 million MT.

Since 1984, the U.S. annual production rate of phosphate rock has averaged at about 40 million MT (TFI89). Under the assumption that 8 percent of this quantity is used for the production of elemental phosphorus, 3.2 million MT of phosphate rock are processed annually in thermal plants (TVA86, EPA89a). Since the thermal process yields about 0.07 MT of elemental phosphorous per MT of phosphate rock, approximately 3.0 million MT of slag were generated yearly by all U.S. thermal plants. The annual average slag generation rate is therefore estimated to be about 600 thousand MT per plant.

The quantity of phosphate rock used in domestic elemental phosphorus production actually decreased from 3.2 million MT in 1986 (DOI87) to less than 3 million MT in 1988. In 1988, the total industry-wide production of elemental phosphorus by the five plants listed in Table B.2-2 was 311,000 MT (EPA90a). The aggregate industry-wide generation of slag by the five plants was approximately 2.6 million MT, yielding a facility average of about 526,000 MT per plant (EPA90a). The sector-wide ratio of metric tons of slag to metric ton of elemental phosphorus was 8.4 in 1988.

The predominant management practices for this waste material include sale of the slag for use as an aggregate in road and building construction material and storage or disposal of the slag in waste piles. In 1988, the quantity of slag sent to disposal waste piles at the five facilities ranged from none to more than 500,000 MT per facility, averaging 320,000 MT. As of 1989, stockpile areas at the five facilities ranged from 5 to 38 hectares (12 to 95 acres) per facility. The total quantity of slag accumulated in these piles in 1988 ranged from 1.5 million MT to 21 million MT per facility (EPA90a).

The amount of slag produced annually by elemental phosphorus plants is small compared to the amount of phosphogypsum produced annually by phosphoric acid plants. Over 13 metric tons of phosphogypsum waste is produced for each metric ton of slag produced. Thus the predominant waste for this sector is phosphogypsum.

2.3.2 Phosphogypsum and Slag Utilization

Since there are large quantities of phosphogypsum waste, the industry would like to encourage the use of phosphogypsum in order to minimize the disposal problem. Currently, phosphogypsum is being used in several commercial applications with additional research being conducted by such groups as the Florida Institute of Phosphate Research (FIPR) in order to identify new applications and expand existing ones. Current applications include: 1) as fertilizer (see Chapter B.3), 2) as conditioner for soils where peanuts and other crops are grown, 3) as backfill for roadbed material, 4) as additives to concrete and concrete blocks, and 5) thermal processing to produce sulphur (LLO85). Research is being done on the use of phosphogypsum in ceramic products, as anti-skid aggregate, concrete aggregate, and soil conditioners (EPA85a, LLO85). During 1988, a total of 1.1 million metric tons of gypsum

were used as a soil conditioner and fertilizer (TVA83). Almost 20 percent of this gypsum was from phosphogypsum stacks. Over 86 percent of the gypsum was used in three states, namely California, Georgia, and North Carolina. Other states where significant quantities of gypsum were used include Arizona, Florida, and Virginia.

The use of phosphogypsum in Europe and Japan has been much more widespread than in the U.S., due to the absence of low-cost natural gypsum and lack of long-term storage space. These countries have used phosphogypsum extensively in cement, wallboard, and other building materials (LLO85). Phosphogypsum was used by a New Jersey-based company that manufactured wallboard, partition blocks and plaster for distribution in the northeastern United States between 1935 to 1946 (FIT78).

Because of elevated levels of radionuclides in the use of phosphogypsum, especially in building construction materials, could result in elevated radiation exposures to members of the general public. O'Riordan et al. suggest that dose estimates generated to characterize exposure from phosphogypsum wallboards are an order of magnitude lower than suggested guidelines (ORI72). However, Fitzgerald and Sensintaffar (FIT78) indicate that the assumptions used to model the exposures were probably not realistic, that previous studies may have led to underestimations, and that further evaluations are necessary to take into account current building practices. It was also recommended that a survey be conducted of a statistically acceptable number of homes built with phosphogypsum materials.

A modular structure consisting of precast ferrocement-sandwich panels was constructed as part of the FIPR's ongoing research to establish commercial uses for phosphogypsum (CHA87). The ferrocement panels were made using 50 percent phosphogypsum, 25 percent cement, and 25 percent fine aggregate. Radon levels were measured inside the structure using the worst possible ventilation conditions by making the structure as air-tight as possible. Measurements were made using both track-etch detectors and radon gas analyzers. Radon levels were noted to range from 2.9 to 5.6 pCi/L (averaging 4.1 pCi/L) using track-etch detectors and from 1.1 to 15.9 pCi/L (averaging 5.1 pCi/L) using a radon gas analyzer. Diurnal variations of radon levels were observed with maximum levels occurring when the walls were at their lowest temperature (CHA87).

The Texas Department of Health has authorized the use of phosphogypsum mixed with fly ash and/or cement as a base for roads, parking lots, and storage areas, or as underground bedding for pipes and utility lines (ROE87). The environmental assessment concludes that such non-domestic applications do not endanger public health. The State of Florida is considering a similar action following a review of such kinds of applications. Phosphogypsum has been used, on a limited basis, in the manufacture of wallboard as well as in the manufacture of building materials, such as cements, concrete blocks, and panels. However, because of treatment processes, the final physical properties of phosphogypsum renders it uncompetitive with natural gypsum (BRU80).

In Japan, phosphogypsum is used in the manufacture of cement, gypsum board, and plasters (MIY80). All of the phosphogypsum is used since the Japanese do not have a source of natural gypsum. With phosphogypsum being used in other countries, the EPA has conducted a survey of such uses in both Europe and Japan to characterize the potential radiation hazards associated with such uses (FIT78, LLO88). Radiation exposure estimates were reported to range from 100 to 400 mRem/year when used in wallboards. The Europeans are considering the introduction of building codes which would prohibit the use of materials having more than 25 pCi/g; control the use of materials between 10 and 25 pCi/g; and omit regulatory controls of materials with less than 10 pCi/g (LLO88).

The Florida Institute of Phosphate Research is currently studying the impact of Ra-226 uptake in vegetables grown on reclaimed lands (FIP88). Based on a recent study of radioactivity in foods grown in a reclaimed clay settling area, a hypothetical individual is estimated to receive a dose of 0.3 mrem per year more than an individual obtaining food from unmined lands.

Most of these applications typically involve only small quantities of phosphogypsum. It is not conceivable, within the foreseeable future, to expect a sudden increase in the use of phosphogypsum in a wide array of commercial products or applications. The physical properties of phosphogypsum make it uncompetitive with natural gypsum since the former contains wastes and impurities. Suggestions have been proposed to modify the beneficiation process to yield phosphogypsum with less impurities and improved properties making it a more desirable construction material (MIY80, HAB86, MOI80). Phosphogypsum has to be transported over long distances to gypsum manufacturing plants since such facilities are not

typically located near market areas. Other things being equal, the added transportation cost makes phosphogypsum uncompetitive unless natural gypsum is also transported over similar distances.

Slag waste from elemental phosphorous plants has been used in a variety of applications, principally in Idaho and Montana. An evaluation completed by the EPA and the Conference of Radiation Control Program Directors has indicated that slag materials have been put to a wide variety of applications (CRC81, EPA83). Most of these applications have included using slag as an aggregate in concrete and asphalt. Other applications have included the use of slag in railroad ballasts, as casting material for highway structures, in roadbed fill and as backfill, in road gravel, and as a stabilization material for stockyards. Slag materials have also been extensively used in the construction of streets, sidewalks, parking lots, playgrounds, schools, homes, churches, and other public buildings. In Florida, slag has been used on roofs and in septic tank fields. It has also been used in manufacturing rockwool insulation. Slag materials have also been proposed for use in manufacturing ceramic tiles.

Because of elevated levels of radioactivity in elemental phosphorus slag, some states are restricting its use for certain applications. For example, as noted in Section 2.4.3, the State of Idaho has prohibited the use of phosphorus slag as an aggregate in materials used for building construction while still allowing its use in road construction.

2.3.3 Twenty-Year Waste Inventory

Phosphogypsum

Various estimates can be made of the amount of phosphogypsum that may be generated in the U.S. during the next 20 years. These estimates are based on different assumptions about waste generation rates and lead to different conclusions regarding total metric tons of phosphogypsum waste that may be produced. The different estimates are summarized in the following paragraphs.

The total amount of phosphogypsum generated in the U.S. from 1910 to 1981 was estimated at 7.7 billion metric tons (MT) (CRC81). Since 1981, another 350 million MT of phosphogypsum were added to this inventory. Based on current average production rates of phosphoric acid (about 8.7 million MT per year), it is estimated that 783 million MT of phosphogypsum will be produced in the U.S. during the next 20 years (EPA89a). The Central Florida phosphate district alone will produce 640 million metric tons of phosphogypsum in the next 20 years, assuming that 32 million MT of phosphogypsum will be produced each year. By the year 2000, it is estimated that about one billion metric tons of phosphogypsum waste will be stockpiled in Florida alone (CHA87).

As mentioned previously, there are currently 23 wet-process phosphoric acid plants operating or on standby in the United States. A typical phosphoric acid plant is designed to produce about 150,000 MT per year of P_2O_5 (DEV79). Since about 4.5 MT of gypsum are produced for every ton of P_2O_5 , this equates to a typical yearly production of 675,000 metric tons of phosphogypsum waste. Therefore, a typical wet-process phosphoric acid plant would generate 13.5 million metric tons of phosphogypsum in 20 years. If all 23 plants remain in operation, about 311 million MT of phosphogypsum will be produced during the next 20 years.

An EPA report estimates that, for an average wet-process plant, 700 metric tons of P_2O_5 is produced per day (EPA88). This equates to a total of 23 million metric tons of phosphogypsum for the average plant, assuming that the plant operates 365 days per year over a span of 20 years. Assuming that 23 plants remain operational, and production remains steady for the next 20 years, the overall future phosphogypsum inventory will be 530 million metric tons.

According to a Teknekron report (TEK79), 2 million MT of phosphogypsum are produced and stored per year at a generic phosphoric acid plant. This equates to a total 20-year production of 40 million MT of phosphogypsum waste. Again, assuming that 23 plants remain in operation, 920 million MT of phosphogypsum will be produced in 20 years.

Given the wide range of these estimates (from 310 to 910 million MT), it is difficult to predict with a reasonable degree of assurance what the inventory of phosphogypsum will be over the next 20 years. It should be noted that the estimates described in the above

paragraphs incorporate underlying assumptions which cannot always be compared on a one to one basis. Unknown variables include fluctuation in the demand for phosphoric acid, uncertainty in the production of phosphogypsum, and the utilization of phosphogypsum in a variety of applications, and others. There are, however, several important factors which may significantly impact the demand for phosphoric acid in the U.S. The most important factor includes the installation of additional productive capacity by foreign producers. In the U.S., and especially in Florida, the phosphate industry is also competing against limited land and water resources and a growing population. State governments are also imposing additional environmental controls and regulations on the industry. Taken together, these factors will tend to raise production costs, may cause the industry to relocate in other states, move production overseas, or rely on imports.

For this risk assessment, the 20-year phosphogypsum inventory is based on an average annual production rate of 40 million MT. As noted in Section 2.3.1, this is approximately the average rate of phosphogypsum production for the years 1984 through 1988. Thus this production rate already reflects, to a certain extent, the influence of foreign producers and the realignment of the U.S. industry to these competitive forces. The 20-year phosphogypsum inventory is estimated to be 800 million metric tons. This inventory is in addition to the 8 billion metric tons of phosphogypsum already stockpiled at stacks in the 12 states listed in Table B.2-3.

Slag

As was noted earlier, the annual average slag generation rate is on the order of 600 thousand MT per plant. For the purpose of this report, this estimate is used to calculate the 20-year slag inventory since this generation rate reflects current industry practices. As was already discussed above, it is assumed that current practices reflect some of the major factors which have regulated, within the past few years, the productive capacity and growth of the industry. Assuming that the five elemental phosphorus plants currently operating continue in operation, it is estimated that about 60 million MT of slag waste will be generated during the next 20 years.

Phosphoric Acid Scale

Phosphoric acid scale is assumed to be generated at the rate of about 6 m³ per year (MAR88). No attempt is made to account for the fact that some of the scale waste is disposed with phosphogypsum in a mixed or diluted form. Assuming that all 23 phosphoric and facilities generate scale in equal amounts, the estimated 20-year inventory of this waste is about 3,000 m³. This volume is very small compared to the volumes of phosphogypsum and elemental phosphorus slag expected to be generated during this period.

2.4 RADIOLOGICAL PROPERTIES OF PHOSPHOGYPSUM AND SLAG

2.4.1 Radionuclide Concentrations of Phosphogypsum and Slag

Uranium in phosphate ores found in the United States ranges in concentration from 7 to 100 pCi/g (DEV79), while thorium occurs at lower concentrations, between 0.1 to 0.6 pCi/g (BLI88). Ions, such as U⁺⁴, Th⁺⁴, Na⁺², and Mg⁺² substitute for Ca⁺² in francolite [Ca₅(PO₄, CO₃)₃F] (GUI75). Because of this ion-exchange property, phosphate rock contains appreciable quantities of uranium and thorium and their decay products. During the beneficiation process, approximately 42 percent of the total radionuclides present in the ore is retained in the marketable rock. The clay slime carries about 48 percent of the radionuclides, and the remaining 10 percent is left in the sand tailings (GUI75). Florida clay slime contains about 45 pCi/g radium-226 (EPA75). Examples of the distribution of the radionuclides found in phosphate ores and their respective concentrations are shown in Table B.2-4.

Phosphogypsum contains appreciable quantities of uranium and its decay products due to the high uranium concentration in the phosphate rock. When the phosphate rock is processed, via acidulation, there is a selective separation and concentration of radionuclides. Most of the radium-226, about 80 percent, follows the phosphogypsum while about 86 percent of the uranium and 70 percent of the thorium are found in the phosphoric acid (EPA88). Typical radium concentrations in phosphogypsum stacks fall within a range of 11 to 35 pCi/g,

Table B.2-4. Radionuclide concentrations in phosphate ores, phosphogypsum, and slag^(a)

Material & Location^(b)	Radionuclide Concentration - pCi/g							
	U-238	U-234	Th-210	Ra-226	Pb-210	Po-210	Th-232	Th-228
Phosphate ore								
1:	27	26	39	26	38	36	0.26	0.52
2:	2.7	2.7	3.6	3.1	4.2	4.1	0.82	1.1
3:	43	44	38	50	50	60	0.07	0.13
4:				60				
5:	32				150	91		
6:	21				26	21		
Slag								
1:	26	26	50	30		0.9	0.93	0.25
3:	11	11	22	12	1.5	0.8	0.87	1.1
4:				56				
7:	41	40	35	48			0.5	
8:	21	20	20	28			0.77	
Ferrophosphorous								
1:	11	8.6	0.51	0.37	0.73		0.08	0.08
3:	9.7	9.8	0.05	0.19	3.9	1.0	0.12	0.21
4:				1.2				
Gypsum^(c)								
9:	6.0	6.2	13	33	26.4	26.4	0.27	1.4

(a) Data extracted from EPA81a, EPA81b, EPA75, EPA88, EPA84, and EPA83.

(b) Location codes:

- 1: Stauffer plant, Montana.
- 2: Monsanto plant, local ore, Tennessee.
- 3: Monsanto plant, Florida ore, Tennessee.
- 4: Florida plants, average.
- 5: Monsanto plant, Idaho.
- 6: FMC plant, Idaho.
- 7: Idaho slag.
- 8: Montana slag.
- 9: Florida phosphate and plants.

(c) Concentration of Pb-210 and Po-210 are based on a radon emanation coefficient of 20%.

with radium decay products falling also in the same range (HEN88, EPA85b, EPA88, LIN78). Some examples of the distribution of the radionuclides found in phosphogypsum and their respective concentrations are also shown in Table B.2-4.

Ferrophosphorus and slag are the principal waste products which carry most of the radionuclides through the elemental phosphorus production process. Because of the high temperatures involved in the process, slag is a vitrified material which binds non-volatile radionuclides. Radionuclides with typically elevated concentrations include uranium and thorium and their decay products. For example, elemental phosphorus slag has been found to contain uranium and thorium in concentrations within the range of 20 to 30 pCi/g and radium-226 in concentrations within the range of 30 to 40 pCi/g (EPA85b, HEN88). Company responses to the EPA's 1989 National Survey of Solid Wastes from Mineral Processing Facilities indicated that concentrations of uranium and thorium in slag range from 23 to 50 pCi/g in plants in Montana and Idaho, and from 2.4 to 45 pCi/g in plants in Tennessee (EPA90b). This same national survey indicated that concentrations of Ra-226 in phosphorus slag ranged from 4 to 32 pCi/g for plants in Idaho and Montana and from 3.2 to 27 pCi/g for plants in Tennessee. Because of the high temperatures involved, some radionuclides are vaporized during the production process. For example, as much as 95 percent of the Pb-210 and Po-210 have been observed in calciner stack releases (EPA81a, EPA81b). Some examples of the distribution of the radionuclides found in ferrophosphorus and slag materials from elemental phosphorus production, and of the concentrations of these radionuclides, are shown in Table B.2-4.

For this risk assessment, the reference waste form is assumed to be phosphogypsum, and the assumed radionuclide concentrations are those considered to be typical of phosphogypsum wastes. Radionuclide concentrations are not adjusted for the presence of slag or phosphoric acid scale wastes. There are several reasons for this. One is that phosphogypsum concentrations are rather conservative since it has been noted that some phosphate ores, and consequently phosphogypsum materials, have lower radionuclide concentrations than those shown in Table B.2-4. The volume of elemental phosphorous slag is also much smaller than that of phosphogypsum. In general, the difference in radionuclide concentrations between phosphogypsum and slag materials is small. Although some measured concentrations of uranium and thorium are higher in phosphate slag than they are in phosphogypsum, measured radium concentrations tend to be about the same. As shown

in Chapter D, the dominant risks to workers and members of the CPG are from radon inhalation, hence the radium concentration is of most concern in the evaluation of health effects.

Because the volume of phosphoric acid scale is small, and because this material is either stored or mixed with phosphogypsum rather than disposed of, this waste stream is not included in this assessment. Some phosphoric acid operations result in scales with significantly higher radionuclide concentrations than those in typical phosphogypsum wastes. The main effect of these higher concentrations would be to increase the radiation exposures to workers. Characterization of these scales and evaluation of associated radiation doses to workers is beyond the scope of this report.

In view of these limitations, the following radionuclide concentrations are assumed for this risk assessment:

<u>Radionuclide</u>	<u>Concentration (pCi/g)</u>
Po-210	26.4
Pb-210	26.4
Ra-226	33.0
Th-228	0.27
Ra-228	0.27
Th-230	13.0
Th-232	0.27
U-234	6.2
U-235	0.3
U-238	6.0

Po-210 and Pb-210 concentrations are derived by applying a radon emanation coefficient of 0.2, assuming that the radionuclides are retained in the phosphogypsum (EPA75). The U-235 concentration is assumed to be 5 percent that of the U-238.

2.4.2 Radon Flux Rates

The radon emanation rate from phosphogypsum stacks is known to be highly variable and depends primarily upon such factors as uranium (and radium) concentrations in phosphate rock, emanation fraction, vegetation cover, porosity, moisture content, presence of standing water, temperature, and barometric pressure. Average radon emanation rates

have been reported to vary from 1.7 to 12 pCi/m²-s, with a mean value of 6.8 pCi/m²-s (EPA89a). The emanation rate, based on measurements made on loose and dry materials, varies even more significantly, ranging from 0.2 to 340 pCi/m²-s (EPA89a, ROE85). Given that phosphogypsum stacks, include surface features such as ponds, ditches, and beaches, the radon exhalation rates over these features is known to be significantly less when compared to loose or dry materials. Radon emanation rates as low as 0.5 pCi/m²-s have been noted on beaches. Radon measurements made over ponds and large bodies of standing water have revealed that radon emanation is essentially insignificant (NCR85, EPA89a). The distribution of phosphogypsum stacks surface features is typically comprised, based on surface area, of: ponds and ditches (60 percent), beaches (15 percent), dry and loose materials (20 percent), and roads (5 percent). Applying these values, an effective radon emanation rate of 5.0 pCi/m²-s is derived for a typical stack.

Radon emanation measurements conducted on Idaho slag indicate that very little radon escapes the vitrified matrix of the slag. Radon exhalation rates of 0.3 and 0.5 pCi/m²-s were observed from intact and crushed slag samples, respectively (EPA83). Measurements taken on two phosphate ore samples revealed radon emanation rates of 57 and 64 pCi/m²-s (EPA83). Radon emanation rates from native soil samples were noted to be higher than that of slag, ranging from 1.7 to 17 pCi/m²-s.

Elevated concentrations of radon in indoor air, caused by the use of elemental phosphorus slag, have been observed in measurements conducted in the Butte, Montana area (EPA83). Indoor radon measurements made in 1,771 homes in Butte showed that 243 homes (14 percent) had indoor radon daughter concentrations above 0.02 working level.* For comparison, EPA's cleanup standards in 40 CFR 192 for soils near inactive uranium mill tailings sites limit the concentration of indoor radon decay products to 0.02 working level.

* A "working level" is any combination of short-lived radon decay products in one liter of air that will result in the emission of alpha particles with a total energy of 130 billion electron-volts.

2.4.3 External Exposure Rates

Radiation surveys conducted on and near phosphogypsum stacks have indicated that elevated radiation levels exist when compared to ambient background exposure rates. For example, measurements made on the top of phosphogypsum piles revealed exposure rates averaging 33 $\mu\text{R/h}$ (TEX78, HOR88). Radiation surveys conducted in areas where large volumes of phosphate ores are stockpiled have revealed exposure rates ranging from 20 to 100 $\mu\text{R/h}$, with an average of 60 $\mu\text{R/h}$ (TEX78). Typical ambient exposure rates due to background radiation varies from 5 to 10 $\mu\text{R/h}$ in Florida (HOR88).

Radiation surveys conducted in Montana and Idaho, where large quantities of slag from elemental phosphorous plants were used to pave streets and incorporated as building materials, have also revealed the presence of elevated exposure rates. Ambient radiation levels in streets paved with slag have been noted to vary from 28 to 50 $\mu\text{R/h}$ (EPA83). In homes, radiation levels as high as 65 $\mu\text{R/h}$ have been noted while measurements made in a church revealed exposure rates as high as 100 $\mu\text{R/h}$ (EPA83, CRC81). Ambient background radiation levels in both states are known to range from 13 to 19 $\mu\text{R/h}$ in areas where it is known that phosphate slags have not been used.

During 1986 and 1987, the EPA conducted a study (EPA90b) to evaluate gamma ray exposures, and the attendant risks, to the populations of Pocatello and Soda Springs, Idaho from the use of elemental phosphorus waste in the construction of roads and buildings. The elemental phosphorus industry in southeast Idaho is about 40 years old. Radioactive slag from plants in Pocatello and Soda Springs has been used as an additive in materials for paving streets and constructing building foundations. In Pocatello, this slag was repeatedly used in paving streets, while in Soda Springs the slag was used in some home foundations. Due to concerns over radiation exposure, the State of Idaho has prohibited the use of phosphorus slag in the construction of habitable structures since 1977, although slag is still used as an aggregate in road construction (EPA90a).

Aerial and ground surveys were conducted at both Pocatello and Soda Springs during 1986 and 1987 to evaluate gamma ray exposures resulting from the use of phosphate slag. A basic set of exposure scenarios was developed and used for both Pocatello and Soda Springs to estimate time spent by individuals of different age groups in different exposure

environments, including time spent inside and outside the home, in the general vicinity of the home, and in the community as a whole. Exposure rates observed at locations included in each scenario were multiplied by the corresponding scenario time intervals, and the results were combined to generate total exposures for individuals in each age group.

The results of this dose and risk assessment are shown in Table B.2-5 for both the average individual and the maximally exposed individual. Exposure to outdoor sources was determined to be the greatest contributor to individual and population doses in Pocatello, due to slag used in street paving. For Pocatello, the net gamma ray doses (the doses with an average background of 12 μ R/hr subtracted) were calculated to be 14 mrem/yr to the average individual and 145 mrem/yr to the maximally exposed individual. These doses were estimated to correspond to lifetime risks of 0.0004 to the average individual 0.004 to the maximally exposed individual, based on 70 years of exposure.

Indoor exposure, resulting from slag in home foundations, was determined to be the greatest contributor to individual and population doses in Soda Springs, Idaho. For Soda Springs, the net gamma-ray doses were calculated to be 52 mrem/yr to the average individual and 205 mrem/yr to the maximally exposed individual. These doses were estimated to correspond to lifetime risks of 0.0014 and 0.0056 to the average and maximally exposed individuals, respectively.

The EPA has noted that the risk estimates presented in the Idaho Radionuclide Study may actually be a factor of two too low (EPA90b). In December 1989, the National Research Council published its Biological Effects of Ionizing Radiation, or BEIR5, Report that offers new risk estimates from radiation exposure. These new risk factors are about twice the risk factors used in the Pocatello and Soda Springs study.

Table B.2-5. Summary of dose and risk results from the Idaho radionuclide exposure study (Source: EPA90b).

Community	Annual Individual Dose (mrem/yr)	Lifetime Risk^(b)
Pocatello		
Average Individual	14	0.0004
Maximally Exposed Individual	145	0.004
Soda Springs		
Average Individual	52	0.0014
Maximally Exposed Individual	205	0.006

-
- (a) Lifetime risk values represent the probabilities of contracting a fatal cancer assuming the individuals remain in their respective communities throughout their entire 70-year lifetime.

2.5 GENERIC SITE PARAMETERS AND SECTOR SUMMARY

2.5.1 Generic Phosphogypsum Stack

The size of the generic phosphogypsum stack is based on data for phosphogypsum production in the State of Florida since, as noted earlier, this state is the major producer of phosphogypsum in the U.S. As shown in Table B.2-3, 20 of the 63 stacks either currently active or idle in the U.S. are located in Florida.

According to Chang, the Central Florida mining district produces 32 million metric tons of phosphogypsum waste per year (CHA87). Currently, there are over 400 million metric tons stockpiled in this district and it is projected that another 640 million MT will be generated during the next 20 years, bringing the total to 1.0 billion MT in Florida alone. However, this estimate does not attempt to account for past and present utilization as well as mined out areas that have been reclaimed. The total current and past utilization rates are unknown, but are probably small. It is assumed that utilization amounts are negligible when compared to the level of uncertainty associated with the data.

It is assumed that the generic site, over its operational life, will share its burden with the total phosphogypsum inventory ever produced in Florida, including the estimated inventory for the next twenty years. As noted, this total inventory is just over 1 billion metric tons. Assuming that the existing 20 Florida sites will remain active or idle and not be subjected to future reclamation, the average site will have a stockpile of about 50 million MT of phosphogypsum. Given this inventory, the volume of the stockpile is 21.3 million cubic meters, assuming a phosphogypsum density of 2.35 g/cm^3 . The resulting dimensions of such a phosphogypsum stack are just under 1,750 m by 1,750 m, based on a 7 m height. The exposed area of such a stack is about 3.0 million m^2 .

2.5.2 Population Exposure

This generic phosphogypsum stack is assumed to be located in central Florida. The population in this area is based on the state's average population density, or 216 persons per square mile (BOC87).

2.5.3 Radionuclide Concentrations

The phosphogypsum radionuclide concentrations, as previously characterized, are used as a basis of the radiological risk assessment. The radionuclide concentrations are not adjusted for the presence of slag. The reason for this approach is the belief that phosphogypsum concentrations are rather conservative since it has been noted that some phosphate ores, and consequently phosphogypsum materials, have radionuclide concentrations that are lower than those shown in Table B.2-4. Finally, the difference in radionuclide concentrations between phosphogypsum and slag materials is not great so that this disparity is not anticipated to skew the results of the risk assessment. These variations are also within the range of uncertainty associated with the data characterizing these waste forms. The reference radionuclide concentrations used in the phosphate waste risk assessment of Chapter D are given in Section 2.4.1.

B.2 REFERENCES

- BLI88** Bliss, Wayne A., Las Vegas Facility, Memorandum to Mr. H. Michael Mardis, Environmental Protection Agency, Washington, DC, February 3, 1988.
- BOC87** Bureau of Census, Statistical Abstract of the United States - 1988, 108th Edition, Department of Commerce, Washington, DC, 1987.
- BOM88** Bureau of Mines, World Demand for Fertilizer Nutrients for Agriculture, Open File Report, OFR 24-88, Department of the Interior, Washington, DC, April 1988.
- BRU80** Bruce, R.B., et al., Gypsum Building Products in North America: Can Phosphogypsum Compete with Alternatives?, Proceedings of the International Symposium on Phosphogypsum, Lake Buena Vista, Florida, November 5-7, 1980, p.89.
- CHA87** Chang, W.F., Reclamation, Reconstruction, and Reuse of Phosphogypsum for Building Materials, Florida Institute of Phosphate Research, Publication No. 01-014-048, 1987.
- CRC81** Conference of Radiation Control Program Directors, Natural Radioactivity Contamination Problems, Report No.2, Frankfort, KY, August 1981.
- DEV79** DeVoto, R.H., and D.N. Stevens, editors, Uraniferous Phosphate Resources and Technology and Economics of Uranium Recovery from Phosphate Resources, United States and Free World, Earth Sciences, Inc., Department of Energy Open File Report GJBX-110(79), 3 volumes, 1979.
- DOI87** Minerals Yearbook 1987, Volume 1, Metals and Minerals, Bureau of Mines, U.S. Department of Interior, Washington, DC, 1987.
- EPA75** Radioactivity Distribution in Phosphate Products, By-Products, Effluents, and Wastes, Technical Note ORP/CSD-75-3, Office of Radiation Programs, Environmental Protection Agency, Washington, DC, August 1975.
- EPA81a** Emissions of Naturally Occurring Radioactivity from Stauffer Elemental Phosphorus Plant, ORP/LV-81-4, EPA, Office of Radiation Programs, Las Vegas, Nevada, August 1981.
- EPA81b** Emissions of Naturally Occurring Radioactivity from Monsanto Elemental Phosphorus Plant, ORP/LV-81-5, EPA, Office of Radiation Programs, Las Vegas, Nevada, August 1981.
- EPA83** Environmental Protection Agency, Evaluation of Radon Sources and Phosphate Slag in Butte Montana, Environmental Protection Agency, EPA 520/6-83-026, Washington, DC, June 1983.

- EPA84** Environmental Protection Agency, Regulatory Impact Analysis of Emission Standards for Emission Standards for Elemental Phosphorus Plants, EPA, Office of Radiation Programs, Washington DC, EPA 520/1-84-025, October 1984.
- EPA85a** Environmental Protection Agency, Report to Congress, Wastes from the Extraction and Beneficiation of Metallic Ores, Phosphate Rock, Asbestos, Overburden from Uranium Mining, and Oil Shale, EPA/530-SW-85-033, Washington, DC, 1985.
- EPA85b** Environmental Protection Agency, Radiation Exposures and Health Risks Associated with Alternative Methods of Land Disposal of Natural and Accelerator-Produced Radioactive Material. (NARM) (DRAFT), Performed by PEI Associates, Inc., and Rogers & Associates Engineering Corp. under EPA Contract 68-02-3878, October 1985.
- EPA88** Environmental Protection Agency, Background Information Document, Radionuclide Emissions from Phosphogypsum Stacks, - Risk Assessment, Washington, DC, 1988.
- EPA89a** Environmental Protection Agency, Draft Environmental Impact Statement for Proposed NESHAPS for Radionuclides-Background Information Document, Volume 2 Environmental Protection Agency EPA 520/1-89-006-1, Washington, DC, February 1989.
- EPA89b** Environmental Protection Agency, 40 CFR 61, National Emission Standards for Hazardous Air Pollutants; Radionuclides; Final Rule and Notice of Reconsideration, Federal Register, Vol. 54 No. 240, December 15, 1989, pp 51654-51715.
- EPA90a** Environmental Protection Agency, Report to Congress on Special Wastes from Mineral Processing, EPA/530-SW-90-070, Office of Solid Waste and Emergency Response, Washington, DC, July 1990.
- EPA90b** Environmental Protection Agency, Radionuclide Exposure Study -- Pocatello and Soda Springs, Idaho, Office of Radiation Programs, Las Vegas Facility, April 1990.
- FIP88** Florida Institute of Phosphate Research, 1988 Annual Report, Bartow, Florida.
- FIT78** Fitzgerald, J.E., and E.L. Sensintaffar, Radiation Exposure from Construction Materials Utilizing Byproduct Gypsum from Phosphate Mining, Nuclear Regulatory Commission, NUREG/CP-0001, Radioactivity in Consumer Products, Washington, DC, August 1978.
- GUI75** Guimond, R.J., and S.T. Windham, Radioactivity Distribution in Phosphate Products, By-products, Effluents, and Wastes, Environmental Protection Agency, Technical Note ORP/CSD-75-3, Washington, DC, August 1975.

- HAB86** **Habashi, F., et al., The Hydrochloric Acid Route for Phosphate Rock, Journal of Chem. Tech. Biotechnology, Vol. 38, pp. 115-126, 1987.**
- HEN88** **Hendricks, Donald W., NORM in Mineral Processing, Published in CRCPD Publication 88-2, 19th Annual National Conference on Radiation Control, May 18-21, 1987, Boise, Idaho, Conference of Radiation Control Program Directors, Frankfort, Kentucky, 1988.**
- HOR88** **Horton, T.R., et al., A Study of Radon and Airborne Particulates at Phosphogypsum Stacks in Central Florida, Environmental Protection Agency, EPA 520/5-88-021, October 1988.**
- KEA88** **Keaton, Harlan W., Naturally Occurring Radioactive Materials in the Construction Industry and Current Building Codes, Published in CRCPD Publication 88-2, 19th Annual National Conference on Radiation Control, May 18-21, 1987, Boise, Idaho. Conference of Radiation Control Program Directors, Frankfort, Kentucky, 1988.**
- LIN78** **Lindeken, C.L., and Coles, D.G., The Radium-226 Content of Agricultural Gypsums, Nuclear Regulatory Commission, NUREG/CP-0001, Radioactivity in Consumer Products, Washington, DC, August 1978.**
- LLO85** **Lloyd, G. Michael, Jr., Phosphogypsum, A Review of the Florida Institute of Phosphate Research Programs to Develop Uses for Phosphogypsum, 1985, Bartow, Florida.**
- LLO88** **Communication with Mr. Lloyd, G. Michael, Jr., Florida Institute of Phosphate Research, Bartow, Florida, with SC&A, Inc. personnel, September 1988.**
- MAR88** **Martel, Chris, telephone conversation with Arthur D. Little, Boston, Massachusetts, on February 3, 1988.**
- MIY80** **Miyamoto, M., Phosphogypsum in Japan, Proceedings of the International Symposium on Phosphogypsum, Lake Buena Vista, Florida, November 5-7, 1980, p.573.**
- MOI80** **Moisset, J., Radium Removal from Phosphogypsum, Proceedings of the International Symposium on Phosphogypsum, Lake Buena Vista, Florida, November 5-7, 1980, p. 384.**
- NCR85** **National Council on Radiation Protection and Measurements, Evaluation of Occupational and Environmental Exposures to radon and Radon Daughters in the United States, Report No. 78, Washington DC, May 1985.**
- ORI72** **O'Riordan, M.C., et al., The Radiological Implications of Using By-Product Gypsum as a Building Material, National Radiological Protection Board, Harwell, Didcot, Berks, the United Kingdom, Report NRPB-R7, 1972.**
- REL89** **Relsch, M.S., Phosphorous Producers Enjoying Good Year, Chemical & Engineering News, p.13, July 17, 1989.**

- ROE87** **Roessler, C.E., The Radioactivity Aspects of Phosphogypsum, paper submitted to the Proceedings of the Florida Natural Radiation/Technologically Enhanced Natural Radiation Symposium, Daytona Beach, Florida, May 6-8, 1987.**
- ROE85** **Roessler, C.E., Radon Emissions from Phosphogypsum Stacks, paper presented at the Proceedings of the Eighteenth Midyear Topical Symposium of the Health Physics Society, Colorado Springs, January 6-10, 1985.**
- TEK79** **Teknekron Research, Inc., Information Base (Including Sources and Emission Rates) for the Evaluation and Control of Radioactive Materials to Ambient Air, Vol. 2., Interim Report, prepared for Office of Radiation Programs, Environmental Protection Agency, Washington, DC, July 1979.**
- TEX78** **Texas Instrument, Inc. Central Florida Phosphate Areawide Impact Assessment, Program, Vol.VI: Land, Report prepared for Environmental Protection Agency, Dallas, TX, September 1989.**
- TFI89** **The Fertilizer Institute, Fertilizer Facts and Figures, Washington, DC, 1989.**
- TVA88** **Tennessee Valley Authority, Commercial Fertilizers, TVA/NFCD-85/5, Bulletin Y-207, Muscle Shoals Alabama, December 1988.**
- TVA86** **Tennessee Valley Authority, Fertilizer Trends, TVA/OACD-86/12, Bulletin Y-195, Muscle Shoals Alabama, October 1986.**
- TWN88** **Townsend, F.C., D.G. Bloomquist, S.A. McClimans, and M.C. McVay, Reclamation of Phosphatic Clay Waste Ponds by Capping, Florida Institute of Phosphate Research, Publication No. 02-030-056, 1988, Bartow, Florida.**

B.3. PHOSPHATE FERTILIZERS

3. INTRODUCTION

As discussed in the preceding Chapter, phosphate rock is mined and processed to produce phosphate fertilizers. The major waste product is phosphogypsum. The end product, phosphate fertilizers, while obviously not a waste, contains elevated levels of naturally-occurring radioactivity. Fertilizers are available in three major physical forms, bulk, fluids, and bagged. About 80 percent of phosphate fertilizer consumption is handled in a bulk form. Phosphate is also found in multiple-nutrient fertilizers, which are available in different blends of nitrogen (N), phosphate (P), and potassium (K), usually expressed in varying percentages of N-P-K.

Fertilizers are spread over large areas of agricultural land. The major crops which are routinely treated with phosphate based fertilizers include coarse grains, wheat, corn, soybeans, and cotton. Since large quantities of fertilizers are used in agricultural applications, phosphate fertilizers are included as a NORM material because of their potential for environmental contamination. The use of phosphate fertilizers could eventually lead to an increase of radioactivity in the environment.

In the sections which follow, a description of types of phosphate fertilizers and their agricultural applications are provided to characterize the process by which naturally-occurring radionuclides are introduced into the environment. The description also presents information on current and future phosphate fertilizer production and application rates. This information is used in Chapter D to assess potential exposures to members of the public and critical population groups from the use of phosphate fertilizers.

3.2 PRODUCTION OF PHOSPHATE FERTILIZERS

3.2.1 Phosphoric Acid Production

The primary ingredient in the production of phosphate fertilizers is phosphoric acid. Typically, the phosphate fertilizer plant is co-located with the phosphoric acid production facility.

Phosphoric acid can be produced by a wet process and a furnace process. In the wet process, beneficiated phosphate ore is treated with sulfuric acid. The product of this operation is a slurry that consists of the phosphoric acid solution and a suspended solid, calcium sulfate, commonly known as phosphogypsum. About 95 percent of the commercial phosphoric acid produced by the wet process is used in the production of fertilizers and animal feed, with a small portion used as a feedstock in chemical processing operations (BOM87). Furnace process phosphoric acid production uses elemental phosphorus rather than beneficiated phosphate rock as a feedstock. The major wastes from wet process and furnace process phosphoric acid production -- phosphogypsum and furnace slag -- are described in Chapter B.2, and are, therefore, not considered further in this chapter.

Phosphoric acid production increased steadily between 1965, when the industry produced 3.5 million metric tons (MT), and 1984, when 10.3 million MT were produced (TVA86). After 1984, phosphoric acid production decreased to about 8.4 million MT per year (TFI89), due to lower domestic demand for fertilizer and reduced foreign buying. In 1988, production increased slightly to 9.3 million MT (TFI89), boosted by a recovery in the farm economy. The U.S. phosphoric acid industry also competes on the world market. The industry's share of the world market has steadily decreased since 1984, when it exported 1.1 million MT, to 1988, when only 0.24 million MT of phosphoric acid was exported (TFI89). Phosphoric acid production is tied strongly to domestic and foreign fertilizer consumption rates. Non-fertilizer uses of phosphoric acid have declined steadily since the early 1980's due to strict regulations governing the use of phosphates in household products and a decline in industrial demand (EPA90).

3.2.2 Phosphate Fertilizer Production

Phosphate fertilizers are produced from phosphoric acid and directly from phosphate rock. Nearly all (more than 90 percent) of the phosphate fertilizers produced in the U.S. are produced by a phosphoric acid process. Phosphoric acid can be combined with either ammonia, potassium salts, or additional phosphate ore to produce a variety of fertilizers that include ammonium phosphates, superphosphates, and concentrated liquid fertilizers (DEV79, TVA86). Superphosphate, sometimes called super acid, is typically 70 percent phosphorus oxide (P_2O_5) versus 50 percent for the normal grade (GVA88, TVA86). The distributions of nitrogen (N), phosphate (P), and potassium (K) in fertilizers vary, since there are over 100 multiple-nutrient fertilizer grades (TVA88a). For the fertilizer year ending in June 1988*, the average phosphate contents in multiple-nutrient fertilizer blends were 12.1 percent in N-P-K, 40.3 percent in N-P, and 15.1 percent in P-K (TVA88a).

Some phosphate rock (apatite) is acidulated with a limited amount of sulfuric acid to produce a solid product called normal superphosphate. Dry or bulk fertilizers made from sulfuric acid acidulation are granulated for ease of handling. They are non-hygroscopic and free-flowing, whereas nitrophosphate fertilizers must be coated. Normal superphosphate is directly useable as a plant nutrient since the apatite has been reacted with acid to produce water soluble phosphorus.

3.3 PHOSPHATE FERTILIZER CONSUMPTION

3.3.1 Consumption and Application Rates

The United States is a major producer and consumer of phosphate fertilizers. As can be seen from Tables B.2-1 and B.2-2 of Chapter B.2, major locations for the production of wet process phosphoric acid and elemental phosphorus are the states of Florida and Idaho, respectively. These states are also major producers of phosphate fertilizers.

* A fertilizer year runs from July to June.

Actual and projected use of phosphate fertilizer in the U.S. is shown in Table B.3-1 (BOM88). The yearly demand was higher in the period from 1980 to 1985 than it was in subsequent years because of a depression in the farm economy that resulted in a reduction in crop acreage during the latter part of the decade. Demand for fertilizer is expected to increase because of the recovery of the farm economy which resulted in an increase in crop prices and planted acreage in 1989 (EPA90). The annual average U.S. demand for phosphate fertilizers during the nine-year period, 1980 to 1988, was 4.8 million MT (BOM88).

The data reported in Table B.3-1 reflect the use of phosphate fertilizers on major crops, such as coarse grain, wheat, soy beans, and cotton. Typically a third of the production is used in the corn belt region (GUI88). As can be seen from Table B.3-1, the demand for fertilizer closely parallels the acreage of major agricultural crop production. This acreage has varied between 117 to 142 million hectares since 1980 (BOM88). The average over the past nine years is 129 million hectares. The year to year variation in the productive agricultural acreage is largely due to government programs and subsidies regarding grain production. Farmers are at times encouraged not to grow certain crops and to keep land fallow. Fertilizer application rates have, for obvious reasons, paralleled demand from year to year.

Phosphate fertilizer application rates, during the nine-year period 1980 to 1988, varied from a low of 35 kg per hectare to a high of 41 kg per hectare. The average was 37 Kg per hectare. As can be noted, the average application rate for this period is not significantly different from projected application rates given for 1990 and 1995. For the sake of comparison, other fertilizers are typically applied at higher rates. For example, nitrogen and potash are applied at rates of 100 and 40 kg per hectare, respectively.

The demand for fertilizers varies by states across the U.S., with agricultural states obviously using more fertilizers than others. During the 1987-1988 fertilizer year, 12 top ranking states used nearly 60 percent of the total phosphate fertilizer consumption, as seen in Table B.3-2. Illinois was the top ranking state, using 357 thousand metric tons (MT). As can be noted, Illinois is, however, fourth in agricultural cropland area. In general, the top 12 states applied fertilizers at rates varying from 11 to 39 kg per hectare. The overall average fertilizer application rate of these 12 states was essentially identical to that of the national average, 25 versus 24 kg per hectare, respectively.

Table B.3-1. Trends in phosphate fertilizer demand and application.^(a)

-- Year -- Actual/Projected	Fertilizer Demand (million MT)	Major Crop^(b) Harvested Areas (million Ha)	Application Rates (Kg/Ha)
1980	5.5	134	41
1981	5.6	142	39
1982	5.0	136	37
1983	4.4	120	37
1984	5.2	131	40
1985	4.9	134	37
1986	4.5	126	35
1987	4.2	117	35
1988	4.2	120	35
1990	4.4	125	35
1995	<u>5.0</u>	<u>135</u>	<u>37</u>
Average of Actuals:	4.8	129	37

(a) Data extracted from World Demand for Fertilizer Nutrients for Agriculture - 1988 (BOM88).

(b) Major crops include coarse grain, wheat, soybeans, and cotton.

Table B.3-2. Phosphat : fertilizer consumption 1987-1988.^(a)

Top 12 Ranking States	Fertilizer Consumption (thousand MT)	Crop(b) Land Area (million Ha)	Estimated Rates (Kg/Ha)
1-Illinois	357	9.9	36
2-Iowa	307	11.0	28
3-Texas	208	13.0	16
4-Minnesota	226	9.2	25
5-Indiana	206	5.5	37
6-California	166	4.2	39
7-Nebraska	114	8.1	14
9-Ohio	159	5.0	32
10-Kansas	129	12.0	11
11-Wisconsin	118	4.6	26
12-Michigan	114	3.8	30
12 State Total:	2,258	92.3	Average: 25
U.S. Total:	4,100	168.0	Average: 24

(a) Data extracted from Fertilizer Facts and Figures (TFI89).

(b) Crop land area obtained for Statistical Abstract of the United States - 1988 (BOC87).

Gypsum, including phosphogypsum, is also being used in increasing amounts to fertilize and condition soils. During the 1987 and 1988 fertilizer years, 0.91 and 1.10 million MT of gypsum were used as a soil conditioner, primarily in the states of California, Georgia, and North Carolina (TVA88a). It has been estimated that currently about 1.3 million MT of gypsum are used in agriculture in the U.S. each year (USG90). Of this amount, approximately 220,000 MT (17 percent) is from phosphogypsum stacks. Gypsum is used in agriculture as a source of calcium and sulfur for crops such as peanuts grown in soils that are deficient in these elements. Gypsum is also incorporated into soils to provide sediment control for soils that have been eroded and leached to the point where they have developed a compacted crust. In addition, gypsum is sometimes incorporated into acidic soils to act as a buffering agent. The application rate of gypsum (including phosphogypsum) is higher than that of phosphate fertilizers, typically 2 metric tons per hectare (LIN80). When used as a soil conditioner, gypsum is used at still higher rates, e.g., 20 metric tons per hectare initially, followed with applications of 10 metric tons per hectare every other year. Such high application rates are used in California where much of the Central Valley is characterized by arid and alkaline soils with high salt contents.

When phosphogypsum is used as the source of gypsum, it is sometimes pelletized before being applied to the soil; though the majority of phosphogypsum used for agricultural purposes is taken directly from disposal stacks, transported to local fertilizer companies, and distributed to the farmers. When the phosphogypsum is used as a fertilizer it is simply spread on the top of the soil, whereas when it is used for pH adjustment or sediment control it is tilled into the soil. As previously described in Chapter B.2, phosphogypsum contains elevated levels of radium, thorium, and uranium. Its repeated use as a fertilizer or soil conditioner can result in a significant increase in the concentration of these naturally occurring radionuclides in the soil. The potential magnitude of this increase is discussed in Section 3.4.1.

3.3.2 Twenty-Year Fertilizer Production Estimates

Compared to the other NORM sectors, the fertilizer industry obviously produces a product and not a waste. This product is generated in quantities which nearly match the

demand. The industry also minimizes, for reasons of economics, the amount of fertilizer which may be left in inventory stocks at the end of each fertilizer year. For this report, it is assumed that production will simply match demand. As was noted earlier, the projected demand is estimated to be about 5 million MT for the mid 1990s. Assuming that this demand remains fairly constant over the next 20 years, the total production of phosphate fertilizers will reach about 100 million MT over the next 20 years.

3.4 RADIOLOGICAL PROPERTIES OF FERTILIZERS

3.4.1 Radionuclide Concentrations

Phosphate rock contains elevated levels of uranium, radium, and other naturally-occurring radionuclides. Typical concentrations of uranium and radium in Florida phosphate rock are reported to be about 40 pCi/g (GUI88). Thorium is present at much lower concentrations, typically less than 4.0 pCi/g. The phosphate fertilizer production process causes most of the radium to remain with the phosphogypsum waste, while the majority of the uranium and thorium remain with the phosphoric acid making up the fertilizer. Radionuclide concentrations vary with the type of fertilizer and the production process, with average concentrations ranging from 5 to 20 pCi/g for radium, 20 to 60 pCi/g for uranium, and 1 to 5 pCi/g for thorium (EPA85, GUI88, SCA88).

The release of uranium and radium into the environment is appreciable due to the large volumes of fertilizer used and the relatively high concentrations of naturally-occurring radioactivity. Given U.S. fertilizer application rates and average radionuclide concentrations, it is estimated that in 1984 about 30 curies of radium, 400 curies of uranium, and 10 curies of thorium were introduced into agricultural croplands (GUI88). However, it should be noted that despite high radionuclide concentrations and typical application rates, the incremental presence of these radionuclides in natural soils is still low. It has been observed that the incremental Ra-226 soil activity associated with fertilizer applications is about 0.25 percent that of naturally-occurring radioactivity (UNS82). For example, assuming that 129 million hectares are fertilized to a depth of 10 cm and that 30 curies of radium are introduced in the

soil, the resulting incremental radium concentration is on the order of 0.0001 pCi/g. The total soil concentration due to the three radionuclides noted above is on the order of 0.002 pCi/g, assuming a one time application. By comparison, natural soils contain radium in concentrations ranging from 0.1 to 3.0 pCi/g (NCR87).

Given the different grades (over 100) of fertilizers, it is difficult to identify a fertilizer blend which would typify generic radiological properties. Different blends are obtained by mixing various types of fertilizers, such as ammonium phosphate, normal superphosphate, triple superphosphate, and phosphoric acid. Fertilizers also include other nutrients, such as nitrogen and potassium. The actual radionuclide concentrations in typical agricultural fertilizers are lower than those in phosphate fertilizers because of these other ingredients. Typical radionuclide concentrations reported for the different phosphate fertilizers are:

<u>Fertilizer^(a)</u>	<u>Concentrations (pCi/g)</u>			
	<u>Ra-226</u>	<u>U-238</u>	<u>Th-230</u>	<u>Th-232</u>
Normal superphosphate	21.3	20.1	18.9	0.6
Diammonium phosphate:	5.6	63	65	0.4
Triple superphosphate:	21	58	48	1.3
Monoammonium phosphate	5	55	50	1.7
Phosphoric acid ^(b) :	1	25.3	28.3	3.1
Gypsum:	33	6	13	0.3

(a) Extracted from NUREG/CP-0001 (GUI78).

(b) For acid at 28 percent.

Rather than assume a given blend of fertilizers, the radionuclide concentration is pro-rated to the fertilizer production rate since it is assumed that production must at least meet the demand. The production rates are those of 1988 for normal and triple superphosphates, diammonium, and monoammonium phosphates (TVA88b). The radionuclide concentrations are those characterized by Guimond (GUI78), as shown previously. For example, the average Ra-226 concentration is derived as follows:

<u>Phosphate Fertilizers</u>	<u>Average Ra-226 Concentration (pCi/g)</u>	<u>Production^(a) Rate (000 tons)</u>
Normal superphosphate:	21.3	1,660
Triple superphosphate:	21	1,660
Monoammonium phosphate:	5	7,240
Diammonium phosphate:	5.6	7,240

(a) 1988 production in 1000 short tons.

Applying the average Ra-226 concentrations against the production rates, yields:

$$[21.3(1,660/17,800)] + [21.0(1,660/17,800)] + [5.0(7,240/17,800)] \\ + [5.6(7,240/17,800)] = 8.2 \text{ pCi/g.}$$

Applying this methodology to the other radionuclides, gives the following fertilizer concentrations:

<u>Radionuclide</u>	<u>Concentration (pCi/g)</u>	
	<u>Fertilizer</u>	<u>Soil^(a)</u>
Po-210	5.7	0.0018
Pb-210	5.7	0.0018
Ra-226	8.2	0.0025
Th-228	1.1	0.00034
Ra-228	1.1	0.00034
Th-230	53.0	0.016
Th-232	1.0	0.00031
U-234	55.3	0.017
U-238	55.3	0.017
U-235	2.8	0.00086

(a) Based on a phosphate application rate of 37 Kg/ha, plow depth of 15 cm, and applied for 20 years.

For Po-210 and Pb-210, it is assumed that the radon emanation coefficient is 0.3, meaning that 70 percent of the decay products remain trapped in the material. It is also assumed that U-235 is present at a concentration of 4.9 percent that of U-238 (GUI75). For phosphoric acid and gypsum, it is assumed that the concentrations derived for the

superphosphates (normal and triple) and ammonium phosphates (mono- and di-) are encompassing since gypsum is used less frequently and phosphoric acid is mostly used to make these fertilizers rather than applied by itself.

Since fertilizers are widely spread over large fields and diluted with soil, the incremental radionuclide concentrations in soils are typically much lower than those for fertilizer. Over time, the radionuclide concentrations are expected to build-up and reach an equilibrium with competing removal mechanisms that normally deplete fertilizers from soils. These removal mechanisms include plant uptake, leaching by the infiltration of surface water, and wind and water erosion. The soil concentrations, as calculated above, assume an application rate of 37 Kg per hectare, applied yearly for 20 years. It can be seen that the estimated resulting radionuclide concentrations are very low indeed. The actual soil concentrations would probably be still lower, since these estimates do not account for depletion mechanisms which tend to remove radioactivity from the soil.

In a study of the impact of the use of phosphogypsum as fertilizer (BUR76), data on the radium-226 content of phosphogypsum samples from Florida and Idaho were used to calculate the increase in radium-226 content of soil to which phosphogypsum is applied. The study found that the application of 1 metric ton of 40 pCi/g phosphogypsum to 1 hectare of land, and mixed to a soil depth of 20 cm, would increase the radium-226 content of the soil by 0.0154 pCi/g. Therefore, the application of phosphogypsum for the purpose of sulfur fertilization, assuming an application rate of 2 metric tons per hectare per year (a typical rate of fertilizer application, as discussed in Section 3.3.1) would result in an increase in the soil's radium-226 content of 0.031 pCi/g-year. The application of phosphogypsum for pH control, assuming an average rate of 5 metric tons per hectare per year (a typical rate of application for pH control, as discussed in Section 3.3.1) would result in an increase in the soil's radium-226 content of 0.077 pCi/g-year. Over a period of 20 years, these application rates would cause radium-226 concentrations in the soil to increase by 0.62 and 1.54 pCi/g, respectively, as compared to the typical radium-226 content in soils of 0.1 to 3.0 pCi/g.

This risk assessment is based on fertilizer radionuclide concentrations in soils rather than gypsum concentrations, since the application of fertilizers to soils is more widespread than the application of gypsum, except in some localized areas. Because of the limited use of phosphogypsum as a soil conditioner, and the very widespread use of fertilizers containing

phosphate, the risk from fertilizer application is considered to be limiting in terms of total population health effects.

3.4.2 Radon Flux Rates

Radon emanation rates for phosphate fertilizer are assumed to reflect environmental conditions of typical soils. For example, the NCRP notes that for typical soils the average radon emanation rate is about 0.5 pCi/m²-s per pCi/g (NCR87). The U.S. Nuclear Regulatory Commission cites radon emanation rates for tailings and soils with varying moisture contents, based on work conducted by Tanner and Schiager (NRC80). The reported rates for wet, moist, and dry materials are 0.35, 0.65, and 1.2 pCi/m²-s per pCi/g, respectively. Given that fertilizers are typically introduced into the top soil layer (10-15 cm), the moisture content is expected to be lower, but not completely dry, when compared to soils at greater depths. Soil moisture is removed primarily by evaporation and plant transpiration processes. Based on these considerations and the above-noted radon emanation rates for conditions ranging from moist to dry, a typical fertilizer radon exhalation rate may be on the order of about 1.0 pCi/m²-s per pCi/g in soils.

3.4.3 Radiation Exposure Rates

As was briefly noted above, the use of fertilizer may result in the movement and transport of radioactivity in the environment. Radioactivity may be released with surface water run-off and leaching, resulting in increased levels of radioactivity in lakes and rivers, as has been noted in the Mississippi River water basin (GUI88). Leaching can also result in contamination of ground water aquifers. Elevated levels of radioactivity have also been found in drinking water wells (MOO88). Wind blown dispersion of soil and fertilizers can result in releases of radioactive particulates in air, with subsequent exposures to downwind populations. Radon gas released from the soil and fertilizers may also be carried downwind. Direct external radiation exposures may occur from the fertilizer itself and in areas where airborne deposition of wind blown material has occurred.

Since food crops and animal feed are grown in fertilized soils, radionuclide plant uptake may result from the ingestion of contaminated foods, although investigations have shown that radionuclide intake from such pathways is generally minimal (EIS87, GUI88). Given the application rates noted above, it would take several decades for radium to reach an equilibrium concentration since removal mechanisms, such as surface runoff, downward leaching or migration, and plant uptake, reduce the presence of radium (LIN80, ROE87). It has been noted that these removal processes are in fact more effective since the limiting factor is the presence of salt and not radium in fertilizers (LIN80). Plants have a limited tolerance to salt and the soil would most likely not support plant growth long before the radium concentration becomes critical to plant growth.

External radiation exposures associated with the application of phosphate or gypsum fertilizers are expected to be very low when compared to ambient background levels. Given that the mode of exposure, radionuclides, and source to receptor geometry are the same as that found in environmental conditions, it can be assumed that the resulting radiation doses can be simply scaled down based on empirically derived exposure rate conversion factors. The conversion factors represent exposure rates for typical soils and include the effects of gamma ray scatter, build-up, and self-absorption (NCR76). For example, the conversion factors for the uranium and thorium decay series are 1.82 and 2.82 $\mu\text{R/h}$ per pCi/g , respectively (NCR76). As was noted above, the application of phosphate fertilizers results in soil concentrations which are comparatively lower than that of natural soils. Assuming respective U-238 and Th-232 concentrations of 0.128 and 0.002 pCi/g , the total incremental exposure rate is estimated to be 0.24 $\mu\text{R/h}$. In the United States, ambient exposure rates due to terrestrial radiation are known to range from 3 to 16 $\mu\text{R/h}$ (NCR87).

3.5 GENERIC SITE PARAMETERS AND SECTOR SUMMARY

3.5.1 Generic Agricultural Site

The generic site for this NORM sector is assumed to be an agricultural field since phosphate fertilizers are not stored in stacks or waste piles, but are distributed evenly over vast agricultural croplands. The field is that of an average farm located in the state of Illinois. As was noted earlier, this state uses the most fertilizers. The average size farm in the state of Illinois is 136 hectares (340 acres) (BOC87). For the purpose of modelling ground water infiltration and surface water runoff, it is assumed that the field is situated over an aquifer and next to a surface stream. Assuming a square geometry, the dimensions of the field are about 1,200 meters by 1,200 meters. The plow depth is assumed to be 15 cm. For modelling external radiation exposures, the dimensions are assumed to be large enough such that the source of exposure is due to an infinite plane source.

3.5.2 Population Exposure

The population density is assumed to be that of the state of Illinois, at 210 persons per square mile (BOC87).

3.5.3 Radionuclide Concentrations

Several conservative assumptions have been made in this analysis for characterizing the presence of naturally-occurring radionuclides in soils based on actual concentrations found in most fertilizers. Radionuclide concentrations are estimated assuming repeated soil applications for 100 years. The application rate is based on the higher application rate for phosphate fertilizers. The resulting soil concentration has been estimated using current practices. The radionuclide distribution and the respective radionuclide concentrations in fertilizers and soils used in the phosphate fertilizer risk assessment of Chapter D are given in Section 3.4.1.

CHAPTER 3 REFERENCES

- BOC87 Department of Commerce, Statistical Abstract of the United States - 1988, 108th Edition, Bureau of the Census, 1987.
- BOM87 Bureau of Mines, Minerals Yearbook, 1987 Edition, p. 676.
- BOM88 Bureau of Mines, World Demand for Fertilizer Nutrients for Agriculture, Open File Report OFR 84-88, Department of the Interior, April 1988.
- BUR76 Burau, R.G., Agricultural Impact of Radium-226 in Gypsum Derived from Phosphate Fertilizer Manufacture, October 1976.
- DEV79 DeVoto, R.H., and Stevens, D.N., Editors, Uraniferous Phosphate Resources and Technology and Economics of Uranium Recovery from Phosphate Resources, United States and Free World, Earth Sciences, Inc., Department of Energy Open File Report GJBX-110(79), 3 Volumes, 1979.
- EIS87 Eisenbud, M., Environmental Radioactivity, Third Edition, Academic Press, Inc., Orlando, 1987.
- EPA85 Environmental Protection Agency, Radiation Exposures and Health Risks Associated with Alternative Methods of Land Disposal of Natural and Accelerator-Produced Radioactive Materials (NORM) (DRAFT), performed by PEI Associates, Inc., and Rogers & Associates Engineering Corp. under EPA Contract 68-02-3878, October 1985.
- EPA90 Environmental Protection Agency, Report to Congress on Special Wastes from Mineral Processing, EPA/530-SW-90-070C, Office of Solid Waste and Emergency Response, Washington, DC, July 1990.
- GUI88 Guimond, R.J., and J.M. Hardin, Radioactivity Released from Phosphate-Containing Fertilizers and from Gypsum, Journal of Radiation Physics and Chemistry, Pergamon Press, New York, 1988.
- GUI78 Guimond, R.J., The Radiological Aspects of Fertilizer Utilization, Radioactivity in Consumer Products, NUREG/CP-0001, Nuclear Regulatory Commission, Washington, DC, 1978.
- GUI75 Guimond, R.J., and S.T. Windham, Radioactivity Distribution in Phosphate Products, By-Products, Effluents, and Wastes, Technical Note ORP/CSD-75-3, Environmental Protection Agency, August 1975, Washington, DC.
- LIN80 Lindeken, C.L., Radiological Considerations of Phosphogypsum Utilization in Agriculture, Proceedings of the International Symposium on Phosphogypsum, Lake Buena Vista, Florida, November 5-7, 1980.

MOO88 **Mooney, R.R., Department of Social and Health Services, Olympia, Washington, Letter to Mr. Floyd Galpin, Environmental Protection Agency, Washington, DC, February 3, 1988.**

NCR87 **National Council on Radiation Protection and Measurements, Exposure of the Population in the United States and Canada from Natural Background Radiation, NCRP Report No. 94, Washington, DC, December 1987.**

NCR76 **National Council on Radiation Protection and Measurements, Environmental Radiation Measurements, NCRP Report No. 50, Washington, DC, December 1976.**

NRC80 **Nuclear Regulatory Commission, Final Generic Environmental Impact Statement on Uranium Milling, NUREG-0706, Vol. III, Washington, DC, September 1980.**

ROE87 **Roessler, C.E., The Radioactivity Aspects of Phosphogypsum, Proceedings for the Florida Natural Radiation/Technologically Enhanced Natural Radiation Symposium, Daytona Beach Florida, May 6-8, 1987.**

SCA88 **Sanford Cohen & Associates, Inc., Technical Supplements for the Preliminary Risk Assessment of Diffuse NORM Wastes, Prepared for U.S. EPA under contract No. 68-02-4375, October, 1988.**

TFI89 **The Fertilizer Institute, Fertilizer Facts and Figures, 1989, Washington, DC.**

TVA88a **Tennessee Valley Authority, Commercial Fertilizers, TVA/NFDC-89/5, Bulletin Y-207, Muscle Shoals, Alabama, December 1988.**

TVA88b **Tennessee Valley Authority, North American Fertilizers Capacity Data, Muscle Shoals, Alabama, January 1988.**

TVA86 **Tennessee Valley Authority, Fertilizers Trends, TVA/OACD-86/12, Bulletin Y-195, Muscle Shoals, Alabama, October 1986.**

UNS82 **United Nations Scientific Committee on the Effects of Atomic Radiation, Sources, and Effects of Ionizing Radiation, 1982 report to the General Assembly, United Nations, New York, 1982.**

USG90 **McElroy, C.J., Petition of the United States Gypsum Company for Partial Reconsideration and Clarification, and Opposition of United States Gypsum Company to the Petition for Partial Reconsideration and Request for Stay of the Fertilizer Institute, United States Gypsum Company, February 9, 1990.**

B.4 FOSSIL FUELS - COAL ASH

4.1 INTRODUCTION

There are three major fossil fuels used by electric utilities and industry which have the potential to generate NORM waste. These are coal, oil, and natural gas. Studies have shown, however, that the naturally occurring radioactivity in oil and natural gas is very low and that the radioactivity in the wastes produced by their combustion is negligible (NCR77, BED70, EPA73, EPA89b). Therefore, this chapter only addresses coal ash. Combustion wastes from oil and natural gas are not treated in this report.

About 700 million tons of coal were consumed in 1985 to produce electricity or steam, and it is projected that by 1990 nearly 900 million tons will be consumed by electric utilities and industrial boilers (EPA88). There are over 1,300 coal-fired boilers operated by electric utilities and nearly 60,000 industrial boilers in the United States (EPA84, EPA89a, EPA89b). Electric utilities consume the most coal. In 1987, coal was used to produce 57 percent of the electrical needs of the United States. The balance of these needs were generated primarily by nuclear power plants (18 percent), by oil and gas plants (15 percent), and by hydroelectric plants (10 percent) (EIA88).

The consumption of coal generates large amounts of coal ash which require proper management and disposal, either at the point of use or elsewhere in ash impoundment facilities. Some of the ash may be put to productive use, for example, incorporated in construction materials or used for land management and reclamation. Since coal contains naturally-occurring radioactivity, large quantities of coal ash may present a potential radiological risk to exposed individuals. The degree of risk will depend on the physical and radiological properties of the ash and on whether the ash is disposed or used for some purpose such as incorporation in building materials.

In the sections which follow, a description of coal-fired utility and industrial boilers is provided to characterize ash generation and disposal practices for this NORM sector. The description also presents data on the types and volumes of ash produced, the physical and

radiological properties of ashes, future ash volumes and generation trends, and information about the current and projected uses of ashes in various applications. This information is used to assess potential exposures to members of the general public and the critical population group. A radiological risk assessment is performed (see Chapter D) assuming that the exposed population is residing near a generic coal ash site.

4.2 OVERVIEW OF COAL ASH GENERATION

4.2.1 Coal-Fired, Steam-Electric Generating Stations

In a typical coal-fired boiler, coal is burned and the heat is extracted to generate steam. A mixture of coal and air is introduced into the combustion chamber at the base of the boiler and ignited. Depending upon the type of boiler, the combustion process may take place in a state of suspension within the chamber or on a travelling bed. Simultaneously, in the upper portion of the boiler, water is pumped through a series of tubes. Hot combustion gases transfer heat to the water which leaves the boiler as high-pressure steam (about 2,000 psi) and at high-temperature (about 1,000 deg. F). The steam is used to drive a turbine, which in turn, drives an electrical generator. Low pressure steam leaving the turbine is fed to a cooling system which extracts any residual heat and condenses the steam back to water. Condensed water is collected and recycled back to the boiler where the process is repeated. The Electric generating capacity of coal-fired steam plants typically ranges from 100 to over 1,000 megawatts (thermal) (EPA84, EPA83).

The combustion process results in the generation of ash (about 10 percent of the original volume of the coal) which is collected at the bottom of the boiler and in exhaust stack filters. Nearly all of the ash (about 95 percent) is retained as bottom ash and boiler slag (which together contribute 20 percent), or as fly ash (which contributes 75 percent) trapped in exhaust stack filtration devices.

4.2.2 Industrial Boilers

Industrial boilers are used mainly to produce process steam, generate electricity (typically for the facility's own needs), and for space heating. Industrial boilers are used in virtually every industry from small manufacturing to large production facilities. As with utility coal-fired plants, the consumption of coal is proportional to the size or capacity of the boiler. Over 99 percent of the industrial boilers have a generating capacity of less than 75 megawatts (thermal) (EPA84). Given the varied distribution and application of industrial boilers, three industries typically dominate the consumption of coal. These are the chemical, paper, and metal fabrication (steel and aluminum) industries. These three industries consumed nearly 90 percent of the total coal used by industrial boilers in 1974 (EPA84).

4.3 COAL ASH GENERATION

4.3.1 Production of Coal Ash

Coal ash is formed when coal is burned in boilers that generate steam for power production and in industrial boilers. The amount of ash that is produced depends on the mineral content of the coal and the type of boiler. During the combustion process, some of the ash is entrained with hot flue gases to form fly ash. The remainder of the ash, which is too large or heavy to be entrained, settles to the bottom of the boiler to form bottom ash. Liquid slag is formed when the ash melts under the intense heat. Modern furnaces that burn pulverized coal generate more fly ash than stoker boilers because the combustion process takes place in a state of suspension, rather than in a bed (EPA88, EPR88, EEI88). Eisenbud estimates that furnaces burning pulverized coal release 70 percent to 85 percent of the coal ash content as fly ash (EIS87). Stack filtration devices, such as electrostatic precipitators, bag houses, and scrubbers are routinely used to reduce (typically by at least 95 percent) fly ash emissions to the atmosphere. A small fraction of the fly ash, typically 2 percent to 5 percent of the total amount of fly ash produced, is released into the air.

An estimate of the relative proportions of the different types of ash produced in modern furnaces that burn pulverized coal is:

Fly ash:	74 percent
Bottom ash:	20 percent
Boiler slag:	6 percent

These values, based on 1984 data, are believed to be typical of the ash distribution for currently operating furnaces and those that will operate for the next decade (EPA88).

The typical natural content of minerals in coal used in the U.S. ranges from about 3 percent to 30 percent, with an average of about 10 percent depending upon the mining region from which the coal originates (EPA88, ACA86a). Some utilities are selecting coal with lower mineral (or ash) content to meet particulate emission standards. In other instances, utilities reduce the ash content by washing the coal. Washing can reduce the ash content by as much as 50 to 70 percent (EPA88). The 1985 representative ash content of coals used by utilities ranged from a low of 5.9 percent to as high as 29.4 percent, with a national average of 10.5 percent. The average ash content of coal burned has also decreased steadily since 1975 from about 14 percent to the current value of 10.5 percent (EPA88, ACA86a). The ash content has been predicted to remain at about 10 percent until the end of the century (EPA88).

Coal ash is categorized as Class F or C. Class F ash is generated by the combustion of bituminous coal while Class C ash is associated with lignite and sub-bituminous coals. Class F ash is characterized by higher amounts of silicon, aluminum, iron, and a lesser amount of calcium when compared to Class C ash. Typically, these elements make up about 80 to 90 percent of all of the constituents of coal ash. The principal constituents of coal ash are listed in Table B.4-1.

Actual and projected ash production rates are shown in Table B.4-2. As can be noted, the yearly production rate almost tripled between 1966 and 1987. The average yearly production rate, since 1966, is 50.2 million metric tons. More recently, the average yearly production rate over the past 10 years from 1977 to 1987, is 61.5 million MT. In 1987, the

Table B.4-1. Constituents of coal ash.
(Source: ACA86a)

Constituents^(a)	Typical Fraction (%)^(b)	
	Bituminous Class F	Sub-bituminous Lignite Class C
Silicon	45.7	34.9
Aluminum	26.0	18.9
Iron	17.1	5.2
Calcium	3.8	24.0
Sulfur	2.6	2.0
Potassium	1.5	0.4
Titanium	1.2	1.4
Magnesium	1.2	4.2
Sodium	0.6	2.4
Phosphorous	0.3	1.7

(a) Oxide form.

(b) Percentage for each constituent is rounded off.

Table B.4-2. Actual and projected yearly ash (including fly ash, bottom ash, and boiler slag) production rate.

Year of Production		Production Rate (millions of MT)
Actual^(a)	Projected^(b)	
1966		22.9
1967		25.0
1968		26.9
1969		28.8
1970		35.6
1971		38.9
1972		42.0
1973		44.7
1974		54.0
1975		54.4
1976		56.2
1977		61.5
1978		61.8
1979		68.2
1980		60.2
1981		62.0
1982		59.3
1983		57.9
1984		62.8
1985		59.1
1986		60.6
1987		62.5
	1988	73.0
	1989	75.0
	1990	77.0
	1995	90.0
	2000	100.0
	2005	110.0
	2010	120.0

(a) Based on American Coal Ash Association, Inc. yearly data sheets for fly ash, bottom ash, and boiler slags only.

(b) Projected rates are based on past trends (1966 to 1987) using linear regression. All values are rounded off.

combustion of coal in utility and industrial boilers generated 62.55 million metric tons of coal ash and slags and 12.89 million MT of sludges (ACA87a). The distribution of ash and sludge production (as rounded off) are as follows:

<u>Ash Type</u>	<u>Quantity^(a)</u>
Fly ash:	45.0
Bottom ash:	13.0
Boiler slag:	3.7
Sludges:	13.0

(a) In million metric tons.

Over the past 13 years, the yearly increase in ash generation has averaged 2.6 percent. This increase in ash production rate parallels the increase in the demand for electricity during the same period. The demand for electricity over the period from 1973 to 1986 grew at an average annual rate of 2.5 percent per year (NER87).

Although there is some uncertainty over the amount of coal which will be used by electric utilities, it is predicted that coal-fired power stations will still produce the major share of the nation's electrical capacity (EIA88). There are many factors which can affect the amount of coal consumed. Some factors include economic growth rates, demand for electricity, oil and gas prices, types of available technology, and regulatory constraints on waste disposal and airborne emissions. It is, however, reasonably prudent to assume that utilities will continue to use coal and generate ash in large quantities into the foreseeable future.

Long term projections predict that by the turn of the century, the yearly ash (including bottom ash and boiler slags) generation rate will vary from 120 to 140 million metric tons (EPA88, EEI88). This report, however, predicts, based on current trends, that by the year 2000, the yearly generation rate will be about 100 million MT and reach 120 million MT by about 2010 (see Table B.4-2).

The generation of ash is also known to vary by region throughout the United States. Based on an Electric Power Research Institute (EPRI) study, the distribution of fly ash is

predominantly governed by the number and size of coal-fired boilers located in each state. Table B.4-3 presents the total quantity of fly ash produced from all states within the 9 EPRI regions. As can be noted, in 1984 two regions (East North Central and South Atlantic) generated over 40 percent of the fly ash produced nationwide (EPR88). To date, this information is still deemed to be valid (MIL89). These two regions combined include a total of 13 states. The total quantity of ash generated by region varies from a low of 0.25 million MT in New England to a high of 11 million MT for the South Atlantic region. The average per state, excluding Alaska and Hawaii is just under 1 million MT.

4.3.2 Coal Ash Disposal

The majority (typically 70 to 80 percent) of the coal ash produced is disposed in impoundment and landfill facilities either on or offsite (EPA88). The remainder is recycled in a variety of commercial products or used by the ash producer for internal applications. Ashes are usually placed into dry landfills or ash ponds. Sluiced ashes and flue gas desulfurization sludges are stored temporarily in ponds for dewatering to be later transported to a dry landfill. A typical ash disposal landfill may be anywhere from 30 to 60 hectares in size (1 hectare is approximately 2.5 acres) (EEI88, EPA88). An ash pile of this size is assumed to support the disposal needs of a modern power plant with a capacity that ranges from about 500 MW (thermal) to 1,000 MW (thermal). The size of a disposal area can range anywhere from 4 to 25 hectares with some facilities using disposal areas as large as 80 hectares. At the other extreme, one site was reported to have a landfill facility of 177 hectares (438 acres) (EPA88). In order to meet particulate emission standards, ashes are generally disposed of in smaller areas or cells. Smaller active areas may use as much as 8 hectares and, on the average, are comprised of about 2 to 4 hectares (NOV89a). The depth of the ash bed on closure may be as much as 9 m (30 ft) (EPA88).

The Edison Electric Institute indicates that, based on a 1989 survey, there are 305 off-site coal-ash landfills and surface impoundments (EEI89). It is also believed that there are about 900 on-site disposal facilities. Of this total, the status of about 200 facilities is uncertain as to its type, ownership, and whether or not such facilities are still active.

Table B.4-3. Regional fly ash production and utilization-1984^(a)

EPRI Region and States	Fly Ash Produced		Fly Ash Utilized	
	Millions of MT	Percent of Total	Millions MT	Percent Used
1. New England ME, NH, VT, MA CT, and RI.	0.254	0.5	0.09	35.8
2. Mid Atlantic NY, PA, and NJ.	4.77	10.3	0.83	17.3
3. East North Central WI, MI, IL, IN, and OH.	8.99	19.3	1.42	15.8
4. West North Central ND, MN, SD, NE, IA, KS, and MO.	4.87	10.5	1.03	21.1
5. South Atlantic DE, MD, VA, WV, NC, SC, GA, and FL.	11.0	23.7	2.15	19.5
6. East South Central KY, TN, MS, and AL.	4.80	10.3	0.94	19.6
7. West South Central OK, AR, TX, and LA.	5.86	12.6	1.64	28.0
8. Mountain MT, ID, WY, NV, UT, CO, AZ, and NM.	4.61	9.9	1.09	23.6
9. Pacific WA, OR, and CA.	1.36	2.9	0.28	20.7
Totals:	46.5	100.0	9.47	--
Average per State:	0.97	--	0.19	20.4%

(a) Extracted from EPRI CS-4446, March 1988 (EPR88).

4.3.3 Coal Ash Utilization

During 1987, the coal ash industry reported that about 16.6 million MT of ash and 926 thousand MT of sludge were put to use into a variety of commercial applications. These utilization rates represent 26.5 and 7.2 percent, respectively, of the total ash (all forms) and sludge produced in 1987. A fraction of this quantity of ash was also used by the utilities for site reclamation and land use management on utility property. The regional utilization of fly ash is given in Table B.4-3 based on 1984 data (EPR88). Table B.4-4 presents the 1987 utilization breakdown of ash, boiler slag, and sludge based on ash and sludge quantities given above. On a regional basis, the utilization rates vary from a low of nearly 16 percent (East North Central) to a high of about 36 percent (New England). The national average, based on the 48 continental States, is 20.4 percent per state, representing about 0.2 million MT of fly ash per state. This information is still valid although it is based on a 1984 survey conducted by EPRI (MIL89).

A review of Table B.4-4 indicates that in terms of high volume utilization, the bulk of the fly ash, bottom ash, and boiler slags are used as substitutes in cement and concrete, structural fills, for snow and ice control, and as blasting grits and granules. Sludges are used to manufacture wallboard, but the total volume used is minimal compared to the total production. Ranked in decreasing order of utilization, the consumption or utilization of ashes and sludges is distributed as follows:

Boiler slags	59.2 percent
Bottom ash	32.4 percent
Fly ash	22.0 percent
Sludges	7.2 percent

The coal ash industry (American Coal Ash Association), in a 1986 report, has indicated that it foresees a broader range of applications and uses for ash (ACA86a). Such applications include the use of greater volumes in existing applications as well as utilization in new and emerging technologies (ACA87b, ACA88, BOR89, NOV89b).

Table B.4-4. Ash and sludge utilization breakdown for 1987^(a).

Application	Utilization - Percent of Production^{b,c)}			
	Fly Ash	Bottom Ash	Boiler Slag	Sludge
• External Markets:				
- Cement/concrete	57.3	16.9	4.9	0.07
- Structural fills	1.6	4.8	1.7	0.09
- Road base and subbase	2.2	3.5	1.9	0.0
- Mineral filler in asphalt	0.9	0.1	1.6	0.0
- Snow and ice control	0.05	11.8	8.0	0.0
- Blasting grits roof granules	0.0	0.7	64.6	0.0
- Grouting	1.2	0.0	0.0	0.0
- Coal mining application	0.7	7.8	0.0	0.0
- Wallboard	0.0	10.0	0.0	15.3
- Miscellaneous	6.2	6.9	2.1	1.9
Subtotals (%):	70.1	52.4	84.8	17.3
Metric tons (in millions):	7.0	2.3	1.9	0.16

(a) Derived from the American Coal Ash Association data sheet: 1987 Coal Combustion By-product-Production and Consumption.

(b) For fly ash, bottom ash, and slags, the total quantity used in 1987 was 16.6 million MT and 926 thousands MT for sludges.

(c) Percentages and quantities may not add up to 100% or 16.6 million MT due to rounding off.

Table B.4-4. (Continued)

Application	Utilization - Percent of Production^(b,c)			
	Fly Ash	Bottom Ash	Boiler Slag	Sludge
• Internal Utility Use:				
- Cement/concrete	0.0	10.0	0.0	0.0
- Structural fills	12.2	12.0	0.1	0.0
- Road base and subbase	0.3	4.8	0.6	3.4
- Snow and ice control	0.0	1.1	2.8	0.0
- Miscellaneous	17.3	29.7	11.7	79.3
Subtotals (%):	29.8	47.6	15.2	82.7
Metric tons (in millions):	3.0	2.1	0.34	0.77
• Total by-product consumption by product category:				
In percent(%):	22.0	32.4	59.2	7.2
Metric tons (in millions):	10.0	4.3	2.2	0.93
• Total by-product consumption of fly ash, bottom ash, and boiler slags only:				
In percent(%):	<u>26.5</u>			
Metric tons (in millions):	<u>16.6</u>			

- (a) Derived from the American Coal Ash Association data sheet: 1987 Coal Combustion By-product-Production and Consumption.
- (b) For fly ash, bottom ash, and slags, the total quantity used in 1987 was 16.6 million MT and 926 thousand MT for sludges.
- (c) Percentages and quantities may not add up to 100% or to 16.6 million MT due to rounding off.

Fly ash has been used to replace the cement in concrete in the United States since 1910. Typically, fly ash is substituted for 10 to 30 percent of cement (EPR87, EPR88, ACA86a). Depending upon the type of ash used, at ash concentrations greater than 30 percent, concrete may lose its desired strength and setting properties. In some applications where physical strength is not mandatory, the ash content may be increased to as much as 50 percent depending upon the desired properties of such mixtures. Other related uses include the manufacture of concrete construction blocks and preparation of grouting and flowable fill mixtures.

Since the early 1970s, all three types of coal ash have been used in construction projects. Coal ash is used to level out uneven terrain or applied as a stable fill for building construction. Typical applications include sites where shopping malls, housing developments, and industrial parks are planned for construction. Such projects have included the construction of road embankments, runways, public transportation system structures, and soil stabilization. In a 1984 newsletter, the American Coal Ash Association indicated that 40 States have already approved the use of coal ash in road construction and maintenance projects (EPR88, ACA84a). Coal ash has also been used as an additive or filler for asphalt, concrete, and for other aggregate materials. As an asphalt filler, fly ash can comprise up to 12 percent of the total mix.

Other applications include the use of coal ash as an ingredient in intermediate materials used in the manufacture of finished products. Examples are the use of coal ash as an ingredient in the manufacture of concrete blocks and its incorporation in lightweight aggregate such as the granules in roofing felt. The use of coal ash in roofing felt granules is currently limited since the manufacturing capacity is only emerging (ACA86a, ACA88). Commercialization in the United States is under way and it is anticipated that at full production, such plants will eventually be utilizing about 150,000 MT of fly ash per year.

In the examples noted above, coal ash is used directly as a construction material, e.g., as a substitute for natural materials. Other applications include: the use of a fly ash slurry to extinguish fires in coal refuse piles and in deep mines; as flowable fill to stop and control mine subsidence; as a cover to reclaim land strip mines for landfill operations; and, as a solidification media to stabilize sludges and liquid wastes from municipal sewage treatment and industrial facilities (ACA83, ACA88).

For land reclamation, fly ash is typically blended with mining spoils at a rate of 200 to 400 MT per acre (EPR88). For soil amendment, where it is desirable to raise soil pH, fly ash is added at a rate of 50 to 200 MT per acre and mixed to a soil depth of 15 to 30 cm (ACA84b, ACA86b). Other direct applications include the use of boiler slag and bottom ash on icy and snowy winter roads to improve vehicular traction, grit for sandblasting, and pipe bedding and backfill material.

Other emerging applications of fly ash include the construction and sinking of artificial reefs, metal (aluminum and iron) extraction via direct acid leaching, and filler in paints and plastics. Examples of products which may contain fly ash include paints and undercoatings, auto bodies and boat hulls, PVC pipes, battery cases, bowling balls, utensils and tool handles, vinyl floor covering, and shower stalls (ACA86a, AC 88). The use of fly ash is also being tested and evaluated as a refractory for the steel industry and as an additive to explosives.

4.3.4 Twenty-year Coal Ash Inventory Estimates

The 20-year total ash volume is estimated using actual ash generation rates from 1966 to 1987 (Table B.4-2) and projecting the trend out to the year 2010. Assuming that this projection remains valid and that the distribution in the types of ash remains fairly constant, the total ash volume which will be generated over the next 20 years is estimated to be 2,000 million MT. The breakdown between the different types of ash and boiler slag is as follows:

<u>Ash Type</u>	<u>Quantity^(a)</u>
Fly ash:	1,480
Bottom ash:	400
Boiler slag:	120

(a) In million metric tons (MT).

Sludges are not included in these projections because of the paucity of data for past generation trends and utilization rates. Because of air emission standards, it is, however, anticipated that the installation of gas flue desulfurization systems will be common as older boilers are retrofitted and newer plants constructed. The installation of such systems will, in turn, generate more gas flue desulfurization sludges.

Using the 20-year projection with an assumed ash utilization rate of about 30 percent (EPA88), the total ash volume that could be put into productive use is about 600 million MT. It should be noted that this estimate is subject to some variation. For example, past data have indicated that ash utilization rates have typically varied by 10 to 20 percent from year to year. Table B.4-5 presents actual coal ash utilization rates from 1966 to 1987 and projected rates from 1990 to 2010. If the past trend holds true, it is anticipated that by 1990 the utilization rate could be over 30 percent and possibly exceed 40 percent by the turn of the century. These projections assume that the status quo will be maintained while following a moderate growth rate. The utility industry and the American Coal Ash Association (ACA88, EPA88, EEI88) are, however, forecasting higher utilization rates assuming that coal ash will be used more widely in the near future. For example, the American Coal Ash Association is estimating that the use of fly ash as a substitute in concrete could readily be doubled by targeting large construction projects (ACA88, ACA86a). In terms of new applications, fly ash (combined with lime) could be used to stabilize hazardous wastes. Other potential applications involve construction projects or activities while assuming higher utilization rates. Such applications include using ash as a base for road and highway construction, as structural fills, and for land reclamation and soil amendments. Given the potential range of applications which could readily be implemented, the American Coal Association's ultimate objective is to reverse the current disposal (80 percent) and utilization (20 percent) distribution to 80 percent utilization and 20 percent disposal (BOR89). It should be noted that such a high utilization rate is technically achievable since in Europe high utilization rates (70 percent) are not uncommon (ACA84c). On a local basis, some utilities can achieve utilization rates as high as 80 percent, but such demands are typically met by stockpiling ash over several years in anticipation of future needs or even "mining" closed ash impoundment or landfill sites (ACA84d, BOR89, NOV89b).

The EPA, in its 1988 Report to Congress, concluded that a utilization rate of about 30 percent is realistic (EPA88). The EPA has also indicated that it encourages the utilization of coal combustion wastes as one method to reduce the amount of waste which would otherwise require disposal. Given current practices, the Agency also acknowledges that existing utilization practices appear to be done in an environmentally safe manner. Furthermore, it also noted that coal combustion waste streams generally do not exhibit hazardous characteristics under RCRA regulations. The Agency also indicated that it did not

Table B.4-5. Actual and projected yearly ash utilization rate.

Year of Production		Utilization Rate Percent of Production
Actual^(a)	Projected^(b)	
1966		12.1
1967		13.5
1968		17.6
1969		15.3
1970		13.0
1971		20.1
1972		16.3
1973		16.3
1974		14.6
1975		16.4
1976		20.0
1977		20.7
1978		24.1
1979		21.0
1980		18.7
1981		24.0
1982		20.7
1983		20.0
1984		23.1
1985		27.4
1986		21.7
1987		26.5
	1990	21-33
	1995	23-36
	2000	25-39
	2005	27-43
	2010	29-46

(a) Based on American Coal Ash Association yearly data sheets from 1966 to 1987 for fly ash, bottom ash, and boiler slags.

(b) Projected rates are based on past trends (1966 to 1987) using linear regression. Range is based on a fluctuation of 22% (or one standard deviation) from year to year over the period of 1966 to 1987. All values are rounded off.

intend to regulate, under RCRA Subtitle C, the disposal of fly ash, bottom ash, boiler slag, and flue gas desulfurization wastes.

The EPA position, which encourages the utilization of coal combustion wastes, would tend to promote the recycling of such materials in greater quantities and in more diverse applications. Nevertheless, utilities, distributors, and other potential users are concerned that fly ash and its use could become regulated in the near future. Conceivably, legislation or regulations could be enacted which might severely limit the use of coal ash for commercial applications. Such regulations could also leave users open to future litigations. In this context, facilities or sites in which coal ash was once introduced could now be subject to reclamation and clean up requirements (BOY89). Given these competing factors, it is difficult to predict, with any accuracy, future trends in coal ash utilization. Some factors may cause new markets and applications to appear while others may become suppressed or even disappear. These factors, taken together, tend to favor the status quo and maintain a limited, but relatively stable range of applications which tend to throttle high or spurious growth rates (BOY89, CAI89). In view of these uncertainties, a 30 percent utilization factor is assumed for this report.

4.4 RADIOLOGICAL PROPERTIES OF COAL ASH

4.4.1 Radionuclide Concentrations

Coal contains naturally-occurring uranium and thorium, as well as their radioactive decay products. The radioactivity of coal is known to vary over two orders of magnitude depending upon the type of coal and the region from which it has been mined (EPA84, EIS87, BED70, UNS82). The concentrations of U-238 and Th-232 in coal can range from 0.08 to 14 pCi/g and 0.08 to 9 pCi/g, respectively (UNS82). In a review of 800 coal samples characterizing U-238 concentrations, Wagner and Greiner noted that only 0.5 percent of the samples exceeded an activity of 10 pCi/g (WAG82). Beck conducted an evaluation of nearly 1,000 U.S. coal samples and reported average (arithmetic) U-238 and Th-232 concentrations of 0.6 and 0.5 pCi/g, respectively (BEC80, BEC89). The frequency distribution of measured

U and Th contents in coal, however, indicates that concentrations (based on geometric mean) are in fact predominantly lower. For example, the reported mean geometric concentrations of U-238 and Th-232 are 0.34 and 0.26 pCi/g, respectively (BEC80).

The concentration of U-235 in coal is much lower than the concentration of U-238. The natural abundance of the U-235 isotope in natural uranium is 0.72 percent. Assuming that the relative abundance of U-235 to U-238 in coal has this same value, and taking account of the differences in decay rate between U-235 and U-238, for each 1 pCi/g of U-238 in coal there should be about 0.05 pCi/g of U-235.

The radionuclide distributions and concentrations in coal ash are also known to vary significantly (UNS82, BED70, EPA85, EPA83, GRE87). For example, U-238 and Th-232 concentrations have been noted to range from 1.5 to 8 pCi/g and 0.4 to 7.5 pCi/g, respectively (BEC89, BEC80). Average concentrations of U-238 and Th-232 in fly ash are reported to be about 5.4 and 1.9 pCi/g, respectively (UNS82). The radioactivity of fly ash is, therefore, typically higher than that of coal. This enrichment is dependent upon the type of coal used, its ash content, and the type of boiler in which coal is used (UNS82). The enrichment ratio also varies depending upon the elemental form of the radionuclide. For example, enrichment ratios of about 1.3 and 1.4 have been reported for U-238 and Th-232, respectively (UNS82). For other nuclides, much higher enrichment ratios have been observed; up to 2 for Ra-226 and between 5 to 11 for Po-210 and Pb-210. Typically, higher ratios characterize escaping fly ash rather than collected fly ash.

Because of the disparate nature of the data regarding the presence and concentration of radionuclides in ash materials, a simplified approach was used in this assessment to estimate ash concentrations for uranium and thorium, including their decay products. First a limited review of the published literature was conducted to identify commonly reported radionuclides and their respective concentrations (EPA79, EPA83, EPA89b, BEC80, GRE83, GRE87, RAD88, RAD82, STY80, TEK79, UNS82, WAG82, WAG80). Secondly, radionuclide distributions and concentrations were grouped in two categories, fly ash and bottom ash, whenever reported. Thirdly, it was assumed that ash materials were comprised of 80 percent fly ash and 20 percent bottom ash which includes boiler slags. Fourth, coal ash concentrations for each radionuclide were weighted with the distribution noted above to account for the difference in specific activity between fly ash and bottom ash. Fifth, the

radioactivity in sludges was assumed to be essentially identical to that of ash. Finally, the small amount (less than 5 percent) of fly ash which passes through particulate emission systems and becomes airborne was ignored since such ash is not collected or disposed with the other ash materials. For this report, the weighted (80 percent fly ash and 20 percent bottom ash and slag) average radionuclide concentrations are as follows:

<u>Radionuclide</u>	<u>Concentration (pCi/g)</u>
Po-210	7.00
Pb-210	6.80
Ra-226	3.70
Th-228	3.20
Ra-228	1.80
Th-230	2.30
Th-232	2.10
U-234	3.30
U-238	3.30
U-235	0.16

4.4.2 Radon Flux Rates

Several important factors govern the exhalation rate of radon, including mineral form, material density and porosity, particle size distribution, and moisture content. Changing meteorological conditions, such as atmospheric pressure, surface wind velocity, and differences between soil and air temperatures, are known to have pronounced effects on radon emanation rates (NCR85, NCR87). The estimated radon-222 emanation rate is based on the relationship of radium-226 concentration in the soil (pCi/g) to the areal exhalation rate (pCi/m²-s). Given the varied properties of coal ash and factors governing radon emanation, some simplifying assumptions were made in this assessment. Radon-220 (Rn-220) emissions from the Th-232 decay chain are ignored in this report because the dose associated with this noble gas is one or more orders of magnitude lower than that due to Rn-222 (UNS82).

The National Council for Radiation Protection notes that for typical soils, the average radon emanation rate is about 0.5 pCi/m²-s per pCi/g (NCR85). The U.S. Nuclear Regulatory Commission cites radon emanation rates for tailings and soils with varying moisture contents based on work conducted by Tanner and Schiager (NRC80). The reported rates for wet,

moist, and dry materials are 0.35, 0.65, and 1.2 pCi/m²-s per pCi/g, respectively. Schiager suggests a radon emanation rate of 1.6 pCi/m²-s for dry tailings (SCH74) based on the assumption of an infinitely thick, dry tailings bed. Typically, about 90 percent of the source term originates from the first 2 m of material.

Coal ash is generally believed to have a lower exhalation rate than soil since the ash is vitrified (BEC80, WAG81). Radon is thought to be generated and to decay within the particle in which Ra-226 is trapped. Beck reports that fly ash typically has a lower exhalation rate than soil. For example, it is noted that the ratio of the emanation rate to the production rate is about 15 percent for soil, but only about 2 percent for fly and bottom ash (BEC89). Weathering may increase the exhalation rate. If ash particles are subjected to weathering, it is conceivable that the radon exhalation rate would increase over time and reach levels typical to those observed from natural soils (WAG81). Given that coal ash may be disposed in settling ponds, water saturated areas, or be even capped with soil covers, radon exhalation rates may in fact be lower than for soil.

Kalkwarf reports radon emanation coefficients ranging from 0.7 to 9.8 percent for three sets of ash samples (15 measurements) and 1.8 percent for an ash sample from the National Bureau of Standards (KAL85). The results reveal that smaller particles release radon at a greater rate than larger ones. For example, the emanation coefficient for particles less than 0.5 micrometers was about two times higher than that of particles in the range of 11 to 15 micrometers (μm). If the 11 to 15 μm particle size range were used as the cutoff point for characterizing radon emanation rates between large and small particles, the radon emanation coefficient may be assumed to be about 3 percent for particles greater than 11 μm and 4.3 percent for particles less than 11 μm. Ratioing these values to the soil radon emanation coefficient rate of 15 percent and soil exhalation rate of 0.5 pCi/m²-s, a coal ash exhalation rate of 0.13 pCi/m²-s per pCi/g is derived for the purpose of this analysis. This exhalation rate is weighted to reflect the partitioning factor between fly ash (80 percent) and bottom ash and boiler slag (20 percent). A radon emanation coefficient of 4 percent is used in this report.

4.4.3 External Radiation Exposure Rates

No empirical information could be found which characterizes the radiation exposure rates associated with the disposal of coal ash. The EPA has conducted a study to estimate potential doses and risks associated with environmental releases from coal and coal ash piles at utility and industrial facilities with coal-fired boilers (EPA89a). The purpose of this study was to provide background information to consider exempting coal and coal ash piles from the CERCLA reportable quantity (RQ) notification requirements. Conservative models were used to estimate potential radiation doses and resulting health risks to workers standing on the piles and next to the piles (10 m away) and to a nearby resident assumed to reside 100 meters from the piles. The exposure scenarios evaluated in the study were:

- Direct radiation exposure
- Airborne releases of radon and fugitive dusts
- Pile leachate migration to groundwater
- Pile surface water runoff to a nearby stream.

For direct radiation and airborne exposures, the potential doses and risks were analyzed for both the onsite workers and the nearby resident. Potential doses and risks from exposure to contaminated groundwater and to surface water runoff were only analyzed for the nearby resident.

The dose and risk results from postulated exposures to the coal ash pile are summarized in Table B.4-6. The maximum lifetime risk of fatal cancer to a worker standing on an ash pile for eight hours a day, five days per week, 50 weeks per year for 47 years was estimated to be 4.3×10^{-4} ; the maximum lifetime risk to a worker standing next to the ash pile (10 m away) for the same period was estimated to be 1.8×10^{-4} . To put these risks in perspective, a lifetime risk of 4.3×10^{-4} corresponds to an annual dose of 33 mrem and an annual risk of 9.2×10^{-6} for fatal cancers. This annual risk is an order of magnitude lower than the observed risk of job-related accidental death (1.1×10^{-4}) for workers in all industries in the U.S. in 1985. An annual exposure rate of 33 mrem/yr is at the low end of reported exposure rates from natural background radiation in the U.S. For nearby residents, the estimated lifetime health risks, which are calculated to be in the range from 1.6×10^{-5} to

Table B.4-6. Estimated doses and risks from exposures to a coal ash pile (Source: EPA89a).

Exposure Parameter	Yearly Dose (mrem)	Lifetime Risk^a
<u>Worker</u>		
Direct radiation standing on pile	$3.3 \times 10^{+1}$	4.3×10^{-4}
Direct radiation standing near pile	$1.4 \times 10^{+1}$	1.8×10^{-4}
Particulate emissions	7.3×10^{-3}	1.1×10^{-7}
Radon emissions	5.2×10^{-3}	4.3×10^{-6}
<u>Nearby Resident</u>		
Direct radiation	6.1×10^{-1}	1.6×10^{-5}
Particulate emissions	2.2×10^{-2}	3.4×10^{-7}
Radon emissions	2.8×10^{-3}	1.6×10^{-5}
Groundwater	0.0	0.0
Surface water	7.3×10^{-1}	4.6×10^{-6}

-
- (a) For workers, the lifetime risks are for fatal cancers based on exposures starting at age 18 and ending at 65 years of age.
For the nearby resident, the lifetime risks are for fatal cancers based on a 70-year life span.

3.4×10^{-7} , are well within the general range of health risks, 10^{-4} to 10^{-7} , routinely considered to be acceptable within the Superfund program (EPA89a).

4.5 COAL ASH NORM SECTOR SUMMARY

4.5.1 Generic Coal Ash Disposal Site

The reference disposal site is assumed to be located in the Northeast because of the higher population density and coal and ash utilization rates. The quantity of ash disposed on site is representative of overall practices at utility coal-fired plants. The use of coal within the industrial sector, to a certain extent, is also assumed to be implicitly addressed since the quantity of coal consumption and ash generation in this analysis also reflects disposal practices of industrial boilers. Accordingly, it is assumed that by evaluating utilities, the results will also envelope, other things being equal, industrial facilities which are typically much smaller in capacity or size.

The impoundment site is assumed to include all areas where ash is being handled as part of the overall waste management activities, including disposal, grading, capping, etc. During disposal activities, some utilities periodically cover exposed disposal cells with soil caps to reduce wind erosion and minimize fugitive dust emissions. In this assessment, no credit is taken for features or practices which tend to reduce such offsite releases.

The ash contained at the site is assumed to be disposed in a 25-hectare facility totalling 1.3 million MT of ash materials. The ash impoundment is assumed to be square in shape with dimensions of about 500 by 500 meters with a depth of nearly 5 meters, based on an average ash density of 1.2 g/cc (EPR88, EPR87). The ash pile is not capped with a soil cover. The effectively exposed area is about 250,000 m². Depending upon the size of a power plant and the ash content of the coal used, this volume may, in fact, represent more than one year's worth of ash generation.

4.5.2 Population Exposure

The population density near and around the site is estimated to be 780 persons per square mile since the site is assumed to be located near a large urban population center. This population density is based on the average population distribution of four Northeastern States; namely, New Jersey, Connecticut, Rhode Island, and Massachusetts (BOC87).

4.5.3 Radionuclide Concentrations

Because of the disparate nature of the data regarding the presence and concentration of radionuclides in ash materials, a simplified approach is used to estimate ash concentrations for uranium and thorium and their decay products. Radionuclide distributions and concentrations were grouped in two categories, fly ash and bottom ash. It was assumed that ash materials were comprised of 80 percent fly ash and 20 percent bottom ash which includes boiler slags. The coal ash concentrations for each radionuclide were weighted with the distribution noted above to account for the difference in specific activity between fly ash and bottom ash. For the purpose of this report, weighted (80 percent fly ash and 20 percent bottom and slag) average radionuclide concentrations was derived for conducting the risk assessment. The radionuclide concentrations used in the coal ash risk assessment of Chapter D are given in Section 4.4.1.

B.4 REFERENCES

- ACA83** American Coal Ash Association, \$2.1 Million Mine Subsidence Control Project Initiated in Fairmont, Ash at Work, Newsletter, Vol. 15, 1983, No. 2.
- ACA84a** American Coal Ash Association, 40 Highway Departments Utilize Power Plant Ash on Road Construction & Maintenance Projects, Ash at Work, Newsletter, Vol. 16, 1984, No. 1.
- ACA84b** American Coal Ash Association, Iowa Coal Land Being Reclaimed With Class C Ash, Ash at Work, Newsletter, Vol. 16, 1984, No. 5.
- ACA84c** American Coal Ash Association, NAA Message Board by Mr. Tobias Anthony, Executive Vice President, Ash at Work, Newsletter, Vol. 16, 1984, No. 1.
- ACA84d** American Coal Ash Association, Northern States Power Has Remarkable Ash Sales Record, Ash at Work, Newsletter, Vol. 16, 1984, No. 4.
- ACA86a** Coal Ash Book, American Coal Ash Association, 1986.
- ACA86b** American Coal Ash Association, Fly Ash Can Be Effective For Soil Amendment, Ash at Work, Newsletter, Vol. 18, 1986, No. 2.
- ACA87a** American Coal Ash Association, Coal Combustion By-product - Production and Consumption, Data sheets compiled by the ACAA, data set from 1966 to 1987.
- ACA87b** American Coal Ash Association, 1987 Coal Ash Symposium: The Road to Improved Ash Utilization, Ash at Work, Newsletter, Vol. 19, 1987, No. 1.
- ACA88** American Coal Ash Association 1988-1989 Business Plan, Washington, DC, 1988.
- BEC80** Beck, H.L., et.al., Perturbations on the Natural Radiation Environment Due to the Utilization of Coal as an Energy Source, Natural Radiation Environment, CONF-780422, Vol. 2, pp. 1521-1558, 1980.
- BEC89** Letter Transmittal - Paper titled: Some Radiological Aspects of Coal Combustion, Harold L. Beck and Kevin M. Miller, Jan. 13, 1989.
- BED70** Bedrosian, P.H., et al, "Radiological Survey Around Power Plants Using Fossil Fuel", EERL 71-3, Eastern Environmental Radiation Laboratory, U.S. Environmental Protection Agency, Washington, DC, 1970.
- BOC87** Statistical Abstract of the United States, 108th Edition, U.S. Department of Commerce, December 1987.

BOR89 Telephone conversation with Mr. Erast Borissoff, Executive Director, American Coal Ash Association, Washington DC, August 16, 1989.

BOY89 Telephone conversation with Mr. Dave Boyenga, JTM Industries, Atlanta, Georgia, August 14, 1989.

CAI89 Telephone conversation with Mr. Gregg Cain, American Fly Ash Company, Des Plaines, Illinois, August 14, 1989.

EEI88 Edison Electric Institute, Ashes and Scrubber Sludges-Fossil Fuel Combustion By-Products: Origin, Properties, Use, and Disposal, Publication No. 48-88-05, May 1988.

EEI89 Letter from Mr. John J. Novak, Edison Electric Institute, to Ms. Barbara Hostage, USEPA/ERD, dated November 15, 1989.

EIA88 Annual Outlook For U.S. Electric Power 1988 - Projections Through 2000, U.S. DOE Energy Information Administration, DOE/EIA-0474(88), August 24, 1988.

EIS87 Eisenbud, Merrill, Environmental Radioactivity, Third Edition, Academic Press, Inc., Orlando, FL, 1987.

EPA73 Environmental Protection Agency, Assessment of Potential Radiological Health Effects from Radon in Natural Gas, EPA 520/1-73-004, November 1973.

EPA79 Environmental Protection Agency, Radiological Impact Caused by Emissions of Radionuclides into the Air in the United States, Environmental Protection Agency, EPA 520/7-79-006, Draft, August 1979.

EPA83 Environmental Protection Agency, Survey of Five Utility Boilers for Radionuclide Emissions, Prepared by CGA Corporation under EPA Contract 68-02-3168, December 1983.

EPA84 Environmental Protection Agency, Radionuclides Background Information Document for Final Rule, Volume II, EPA 520/1-84-022-2, Washington, D.C., October 1984.

EPA85 Environmental Protection Agency, Radiation Exposures and Health Risks Associated with Alternative Methods of Land Disposal of Natural and Accelerator-Produced Radioactive Materials (NARM) (DRAFT), Prepared by PEI Associates, Inc., and Rogers & Associates Engineering Corp. under EPA Contract 68-02-3878, October 1985.

EPA88 Environmental Protection Agency, Wastes from the Combustion of Coal by Electric Utility Power Plants, Report to Congress, EPA/530-SW-88-002, February 1988.

- EPA89a** Environmental Protection Agency, Technical Background Supplement in Support of Rulemaking Adjustment Activities for Reportable Quantities (RQ) of Radionuclides, prepared by SC&A, Inc. under EPA Contract 68-02-4375, March 1989.
- EPA89b** Environmental Protection Agency, Draft Environmental Impact Statement for Proposed NESHAPS for Radionuclides - Background Information Document, Vol. II, EPA/520-1-89-006, February 1989.
- EPR87** Electric Power Research Institute, Classification of Fly Ash for Use in Cement and Concrete, EPRI CS-5116, Final Report, April 1987.
- EPR88** Electric Power Research Institute, High Volume Fly Ash Utilization Projects in the United States and Canada, EPRI CS-4446, 2nd Edition, March 1988.
- GRE83** Greiner, N.R., Williams, M.D., Wagner, P., Estimation of Radionuclide Releases From Specific Large Coal-Fired Industrial and Utility Boilers, LA-9845-MS, Los Alamos National Laboratory, August 1983.
- GRE87** Greiner, N.R., Wagner, P., Natural Radioactivity in Lignites and Lignite Ash: Final Report, LA-10942-MS, Los Alamos National Laboratory, April 1987.
- KAL85** Kalkwarf, D.R., Emanation Coefficients for Rn in Sized Coal Fly Ash, Health Physics Journal, Vol. 48, pp. 429-436, April 1985.
- MIL89** Telephone conversation with Mr. Mike Miller, Electric Power Research Institute, Coal Combustion System Division, Palo Alto, California, August 17, 1989.
- NCR77** National Council on Radiation Protection and Measurement, Radiation Exposure from Consumer Products and Miscellaneous Sources, NCRP Report No. 56, 1977.
- NCR85** National Council on Radiation Protection and Measurement, Evaluation of Occupational and Environmental Exposures to Radon and Radon Daughters in the United States, NCRP Report No. 78, May 1985.
- NCR87** National Council on Radiation Protection and Measurement, Exposure of the Population in the United States and Canada from Natural Background Radiation, NCRP Report No. 94, December 1987.
- NER87** Electricity Supply and Demand for 1987-1996, North American Electric Reliability Council, November 1987.
- NOV89a** Telephone conversation with Mr. John Novak, Director, Water and Solid Waste Activities, Edison Electric Institute, Washington D.C., January 25, 1989.
- NOV89b** Telephone conversation with Mr. John Novak, Edison Director, Water and Solid Waste Activities Electric Institute, Washington D.C., August 15, 1989.

- NRC80** U.S. Nuclear Regulatory Commission, Final Generic Environmental Impact Statement on Uranium Milling, NUREG-0706, Vol. III, September 1980.
- RAD82** Radian Corporation, A Radiochemical Survey of U.S. Coals and Coal Combustion By-Products, Prepared for the Electric Power Research Institute, Research Project 1620, Final Report, Austin, Texas, September 1982.
- RAD88** Radian Corporation, Assessment of NORM Concentrations in Coal Ash and Exposure to Workers and Members of the Public, Prepared for the Edison Electric Institute (USAWG), Austin, Texas, June 1988.
- SCH74** Schiager, K.J., Analysis of Radiation Exposures on or Near Uranium Mill Tailings Piles, U.S. Environmental Protection Agency, Radiation Data and Reports, Vol. 15, No. 7, pp. 411-425, July 1974.
- STY80** Styron, C.E., An Assessment of Natural Radionuclides in the Coal Fuel Cycle, Natural Radiation Environment, CONF-780422, Vol. 2, pp. 1511-1520, 1980.
- TEK79** Teknekron Research, Inc., Information Base (Including Sources and Emission Rates) for the Evaluation and Control of Radioactive Materials to Ambient Air, Task 2, Vol. 1, Prepared for the Office of Radiation Programs, U.S. Environmental Protection Agency, July, 1979.
- UNS82** United Nations Scientific Committee on the Effects of Atomic Radiation, Sources and Effects of Ionizing Radiation, 1982 report to the General Assembly, United Nations, New York, 1982.
- WAG80** Wagner, P., and Greiner, N.R., Second Annual Report - Radioactive Emissions from Coal Production and Utilization, October 1, 1979 - September 30, 1980, Los Alamos National Laboratory, LA-8825-PR, July 1981.
- WAG81** Wagner, P., and Greiner, N.R., Proceedings of the Workshop on Radioactivity Associated with Coal Use, Held in Santa Fe, New Mexico, September 15-17, 1981, Los Alamos National Laboratory, LA-9106-C, December, 1981.
- WAG82** Wagner, P., and Greiner, N.R., "Third Annual Report - Radioactive Emissions from Coal Production and Utilization, October 1, 1980 - September 30, 1981," Los Alamos National Laboratory, LA-9359-PR, June 1982.

B.5 OIL AND GAS PRODUCTION SCALE

5.1 INTRODUCTION

Both uranium and thorium and their progeny are known to be present in varying concentrations in underground geological formations from which oil and gas are produced (BEL60, JOH73, PIE55). The presence of these naturally occurring radionuclides in petroleum reservoirs has been recognized since the early 1930's and has been used as one of the methods for finding hydrocarbons beneath the earth's surface (MAR87). Uranium and thorium are highly insoluble and, as oil and gas are brought to the surface, remain mostly in place in the underground reservoir. However, radium and the radium daughters are slightly soluble, and under some conditions may become mobilized by the liquid phases in the formation. When brought to the surface with liquid production streams, radium and its daughters may remain dissolved at dilute levels, or they may precipitate because of chemical changes and reduced pressure and temperature. Since radium concentrations in the original formation are highly variable, the concentrations that precipitate out on the surfaces of oil and gas production and processing equipment are also variable and may exhibit elevated radioactivity levels. Scales and sludges that accumulate in surface equipment may vary from background levels of NORM to elevated levels as high as tens of nanocuries per gram depending on the radioactivity and chemistry of the geologic formation from which oil and gas are produced and on the characteristics of the production process.

Since the radioactivity in oil and gas production and processing equipment is generally low and of natural origin, its accumulation and significance were not noted and studied until recently. The problem is now known to be widespread, occurring in oil and gas production facilities throughout the world, and has become a subject of attention in the United States and in other countries. In response to this concern, facilities in the U.S. and in Europe have been characterizing the nature and extent of NORM in pipe scale, evaluating the potential for exposures to workers, and developing methods for properly managing these low specific activity wastes (EPF87, MCA88, MIL87, MIL88).

In 1982, radium and thorium in measurable quantities were found in mineral scales on British oil and gas production facilities in the North Sea. Because large quantities of materials were being handled in the confined working area of offshore platforms, operators developed special work procedures for protection against possible harmful effects of radioactivity. After a review of the situation, the British government and oil industry representatives issued guidelines governing worker safety, material handling, and waste disposal (UK85).

In the U.S., the presence of naturally occurring radioactivity in mineral scale deposits came to the attention of industry and government in the spring of 1986 when, during a routine workover of a well in Mississippi, barium sulfate scale deposited in production tubing was found to contain radium and thorium. Assays of this scale showed 6,000 pCi/g of radium-226 and 1,000 pCi/g of thorium-232 coprecipitated in a barium sulfate matrix (MAR87, MCA88). Because of the concern that some of the contaminated pipes, which had been removed to nearby pipe cleaning facilities, may have contaminated the environment, radiological surveys were conducted by the EPA's Eastern Environmental Radiation Facility. These surveys showed some equipment with elevated external radiation levels and soil contamination.

Both the oil and gas industry and state regulatory bodies, as well as the EPA, are currently examining the problem of identifying and regulating NORM in oil and gas production facilities and equipment. The American Petroleum Institute (API) has sponsored studies to characterize accumulations of naturally occurring radioactivity in oil field equipment and to determine safe methods for its disposal (API89, API90). The API has also formed an Ad Hoc Committee on Low Specific Activity (LSA) Scale which has prepared a draft measurement protocol for identifying producing areas where NORM scale exists (API87). The Part N subcommittee of the National Conference of Radiation Control Program Directors has been working since 1983 to develop model state regulations (Part N of Suggested State Regulations for Control of Radiation) for the control of NORM (CPD87). These model regulations are intended to help individual states develop their regulations in a uniform way such that the regulations are consistent from state to state and with Federal regulations. For example, the state of Texas has proposed NORM regulations that are very similar to the Part N regulations, and Louisiana has regulations for NORM in scales and sludges from oil and gas production. While the regulations are intended to apply generally

to all NORM-containing materials, several parts would apply specifically to the oil and gas industry pipe scale problem.

The American Petroleum Institute (API) has conducted an industry-wide survey of radiation exposure levels associated with NORM in oil production and gas processing equipment (API89). The purposes of the study were (1) to identify the geographic areas of petroleum producing and gas processing facilities having the greatest occurrence of NORM, and (2) to identify items of equipment at these facilities which have the highest NORM activity levels. Over 36,000 individual observations were made in 20 states and two offshore areas by participating petroleum companies using similar equipment and data collection protocols. Radiation exposure levels were measured in units of $\mu\text{rem/hr}$, and the results were reported on survey data sheets provided to all participants. Background radiation levels were also measured and reported for each site in order to differentiate the background effects from contamination effects. The results of this study are summarized in section 5.4.3 of this chapter.

Radium and radium daughters are also known to be present in elevated concentrations in produced waters from oil production operations. In general, these produced waters are reinjected into deep wells or are discharged into non-potable coastal waters. The impacts of elevated concentrations of radionuclides in produced waters are not considered in this risk assessment.

Volumes of NORM scales and sludges from offshore operations are also not included in the inventories presented in this chapter nor in the impacts evaluation of Chapter D. Radiation exposures to workers and to other individuals from offshore operations will be similar to or less than exposures from onshore operations. However, total population impacts might increase slightly if offshore operations were considered in this assessment.

This assessment is limited to NORM in oil and gas production equipment. NORM in gas plant processing equipment is described but is not included in the risk assessment for this sector category because the NORM is generally in the form of Pb-210 surface contamination on the gas plant equipment. Consequently, it does not have a strong radon or gamma emission component. Furthermore, the CPG and collective population effects from

the production equipment are an upper bound to any health impacts from the gas plant equipment.

In the following sections, descriptions are given of the oil and gas production industry, and of the properties of oil and gas scale and sludge waste from production equipment. Also provided are actual and projected amounts of scale and sludge produced by this NORM sector, using the oil and gas production information. This information is used to assess potential exposures and health impacts to members of the general public and critical population groups. A radiological risk assessment is performed (see Chapter D) assuming that both exposed populations reside near a generic site.

5.2 OVERVIEW OF OIL AND GAS PRODUCTION

U.S. crude oil production for the years 1970 through 1987 is shown in Table B.5-1. The highest oil production rate occurred in 1970 at almost 9.64 million barrels per day. Crude oil production has since declined to only about 8.35 million barrels per day in 1987. The production of crude oil in the U.S. is closely tied to the price of crude oil which is determined on a world-wide scale by OPEC countries, and to world demand for crude oil. Thus U.S. oil production is subject to fluctuations that depend on world-wide political and economic conditions as well as on U.S. needs for crude oil.

U.S. production of natural gas for the years 1970 through 1987 is shown in Table B.5-2. Production of natural gas peaked in 1973, and has been declining since that year. In 1987, marketed production of natural gas was about 76 percent of the volume generated in 1973. This decline in marketed production is due both to the more efficient use of natural gas for home heating and to the modernization and improvements in efficiency of industrial furnaces.

Oil and gas production occurs throughout the U.S. and in offshore coastal areas. Table B.5-3 lists the number of operating crude oil production wells in each state and the amount of crude oil obtained from these wells in 1987 (PET88). Table B.5-4 lists the number of

Table B.5-1. U.S. crude oil production. (Source: PET88)

Year	Million bbls/day^a
1970	9.637
1971	9.463
1972	9.441
1973	9.208
1974	8.774
1975	8.375
1976	8.132
1977	8.245
1978	8.707
1979	8.552
1980	8.597
1981	8.572
1982	8.649
1983	8.688
1984	8.879
1985	8.971
1986	8.680
1987	8.349

a A barrel of oil has a capacity of 42 gallons.

Table B.5-2. U.S. natural gas production. (Source: PET88)

Year	Billion Cubic Feet
1970	21,921
1971	22,493
1972	22,532
1973	22,648
1974	21,601
1975	20,109
1976	19,952
1977	20,025
1978	19,974
1979	20,471
1980	20,180
1981	19,956
1982	18,520
1983	16,822
1984	18,230
1985	17,198
1986	16,791
1987	17,150

Table B.5-3. Crude oil production for 1987 by state. (Source: PET88)

<u>State</u>	<u>Number of Producing Wells</u>	<u>Thousand Barrels</u>	<u>State-Wide Rank</u>	
			<u>Number of Producing Wells</u>	<u>Total Production</u>
United States ^a	620,181	3,629,553		
Alabama	875	26,447	24	14
Alaska	1,216	717,415	23	2
Arizona	23	131	31	29
Arkansas	8,398	14,960	13	17
California	45,694	400,808	4	4
Colorado	5,642	33,182	15	11
Florida	122	9,365	28	19
Illinois	32,307	23,980	5	16
Indiana	7,449	3,738	14	23
Kansas	48,051	67,914	3	8
Kentucky	22,974	6,838	8	20
Louisiana	29,758	538,468	7	3
Michigan	4,996	30,352	16	12
Mississippi	2,143	28,833	20	13
Missouri	200	110	26	30
Montana	4,050	25,789	18	15
Nebraska	1,852	6,091	21	21
Nevada	35	3,112	29	25
New Mexico	18,401	86,928	9	7
New York	4,428	710	17	27
North Dakota	3,474	44,271	19	9
Ohio	30,013	12,153	6	18
Oklahoma	101,745	168,688	2	5
Pennsylvania	14,271	3,302	11	24

Table B.5-3. (continued)

State	Number of Producing Wells	Thousand Barrels	State-Wide Rank	
			Number of Producing Wells	Total Production
South Dakota	149	1,644	27	26
Tennessee	648	614	25	28
Texas	198,163	898,237	1	1
Utah	1,785	40,168	22	10
Virginia	29	17	30	31
West Virginia	15,850	5,390	10	22
Wyoming	10,953	134,612	12	6

a Includes 4,487 wells and 295,286 thousand barrels at unspecified locations.

Table B.5-4. Natural gas production for 1987 by state. (Source: PET88)

<u>State</u>	<u>Number of Producing Wells</u>	<u>Billion Cubic Feet</u>	<u>State-Wide Rank</u>	
			<u>Number of Producing Wells</u>	<u>Total Production</u>
United States ^a	253,856	17,155,162		
Alabama	1,000	117,227	16	14
Alaska	87	1,966	25	26
Arkansas	2,847	131,821	12	13
California	1,293	427,935	15	6
Colorado	3,948	162,506	11	10
Florida	0	8,430	27	22
Illinois	238	2,975	23	24
Indiana	808	500	17	28
Kansas	11,280	394,906	8	7
Kentucky	10,493	88,500	9	17
Louisiana	16,647	5,096,369	7	2
Michigan	670	161,629	21	11
Mississippi	749	137,890	19	12
Montana	2,100	46,330	14	19
Nebraska	--- ^b	1,900	--- ^b	27
New Mexico	23,413	818,453	6	4
New York	5,180	36,200	10	20
North Dakota	103	62,857	24	18
Ohio	33,369	191,990	3	8
Oklahoma	26,595	1,987,261	4	3
Pennsylvania	26,000	171,500	5	9
South Dakota	52	2,900	26	25
Tennessee	790	4,500	18	23
Texas	45,552	6,060,960	1	1

Table B.5-4. (continued)

<u>State</u>	<u>Number of Producing Wells</u>	<u>Billion Cubic Feet</u>	<u>State-Wide Rank</u>	
			<u>Number of Producing Wells</u>	<u>Total Production</u>
Utah	497	93,106	22	16
Virginia	685	23,225	20	21
West Virginia	33,950	115,856	2	15
Wyoming	2,104	440,583	13	5

a Includes 3,306 wells and 364,887 billion cubic feet at unspecified locations.
b Not specified.

operating natural gas wells in each state and the marketed production of natural gas from these wells in 1987.

Almost one-third of the operating crude oil production wells in the U.S. are located in the state of Texas which also ranked first in crude oil production in 1987. Five states (Texas, Oklahoma, Kansas, California, and Louisiana) account for two-thirds of the total number of operating crude oil production wells and also produced almost 60 percent of the crude oil in 1987. Alaska, which ranks 24th in the number of producing wells, ranked second in crude oil production in 1987, producing 24 percent of the total barrels of crude oil. There are extensive oil producing areas in the humid coastal regions of Texas, Louisiana, and California, the north slope of Alaska, and some arid regions of northern Texas, Oklahoma, and Kansas. The states of Illinois, Indiana, Ohio, Pennsylvania, and West Virginia rank high in the number of producing wells, with 16 percent of the wells, but low in total production, with only about one percent of production. The wells in these states are mostly stripper wells for the removal of small amounts after the easily recoverable oil has been taken from the reservoirs. Stripper wells do not necessarily result in less of a NORM problem than other producing wells, and may, in fact, result in a greater problem. Stripper wells will produce more water and, therefore, may bring more radium to the surface.

The state of Texas ranks first in the number of producing natural gas wells and also ranked first in marketed production of natural gas in 1987, with 35 percent of the total marketed production. Three states -- Texas, Louisiana, and Oklahoma -- have 35 percent of the producing natural gas wells, and produced more than three-fourths of the natural gas marketed in the U.S. in 1987.

5.3 OIL AND GAS SCALE AND SLUDGE WASTE PRODUCTION

5.3.1 Origin and Nature of NORM in Oil and Gas Scale and Sludge

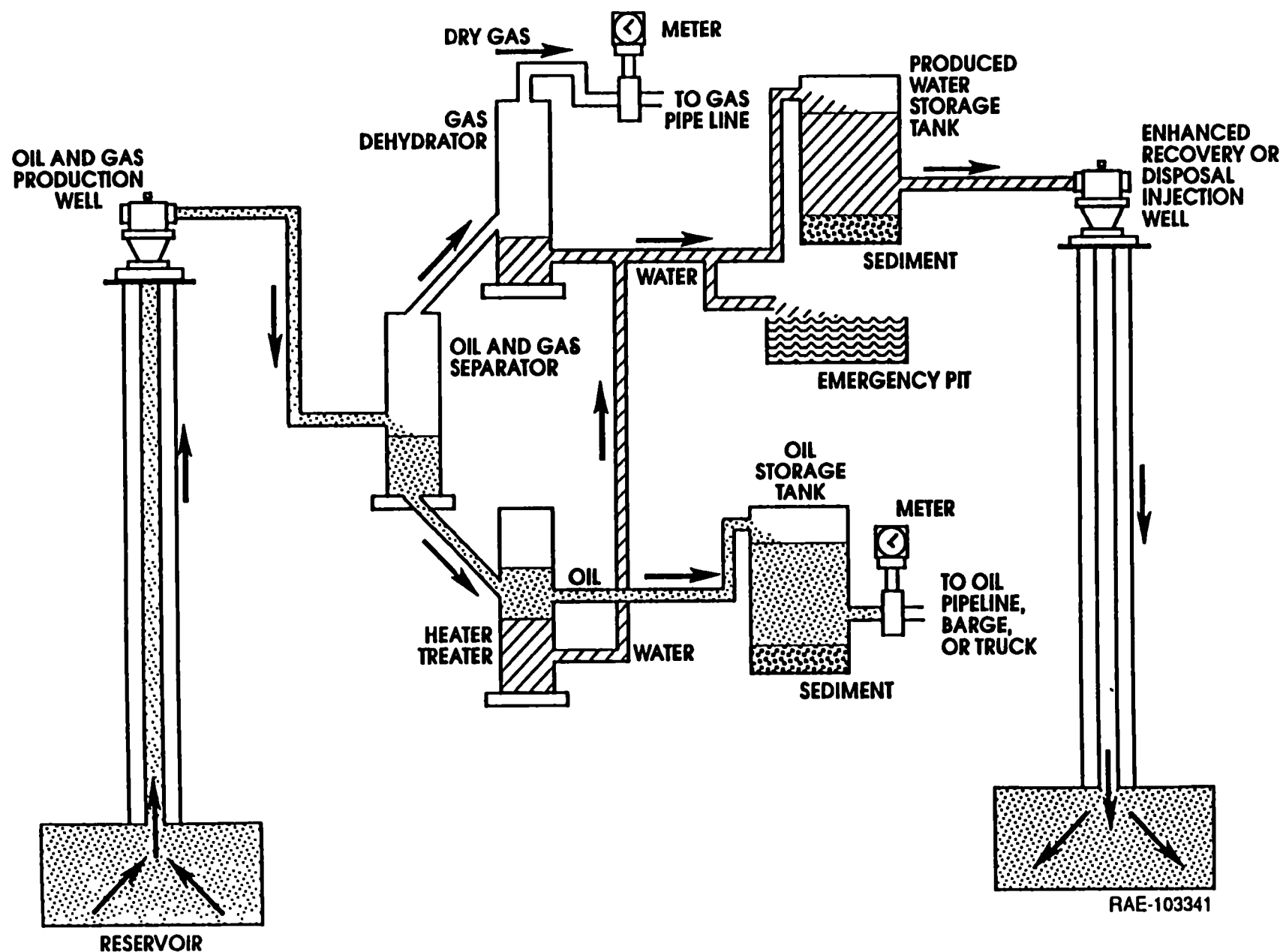
The initial production of oil and gas from a reservoir is usually dry. However, as the natural pressure within the petroleum bearing formation falls, groundwater present in the

reservoir will also be produced with the oil and gas. This formation water contains dissolved mineral salts, a very small proportion of which may be radioactive because of the presence of uranium and thorium and their decay products in the underground formation. Thus, the amount of NORM material from a producing field generally increases with the increases in the amount of water pumped from the formation. The uranium and thorium are relatively insoluble and remain mostly in place. However, radium (Ra-226 and Ra-228 from the uranium and thorium decay chains) is much more soluble and, under some conditions, becomes mobilized by the liquid phases in the reservoir.

The natural formation water will undergo changes in temperature and pressure as it is brought to the surface with the oil and gas and may, under certain conditions, deposit scale and sludge within the oil production system. This scale consists principally of barium, calcium, and strontium compounds (sulfates, silicates, and carbonates). Because the chemistry of radium is similar to that of barium, calcium, and strontium (all are Group IIA elements), radium may also precipitate to form complex sulfates or carbonates.

Deposits in production equipment are generally in the form of thick and hard scale, loose material, or oily sludge. The scale in these chemical matrices is very hard and relatively insoluble. It may vary in thickness from a few millimeters to more than an inch. Scale deposits in production equipment may at times become very thick, and some accumulations have been known to completely block the flow in pipes as large as 4 inches in diameter. Sludge often contains silica compounds, but may also hold significant amounts of barium. Dried sludge which is low in oil content is similar to soil in appearance and consistency, while some sludge remains very oily.

A basic flow diagram for oil and gas production is shown in Figure B.5-1. The oil and gas production stream is processed in a separator where the oil, gas and water are divided into separate streams based on their different fluid densities. Most of the solids in the original fluid stream are removed in the separator and accumulate there. The production stream may be further treated using a heater/treater to separate oil from water and sludge. Most of the NORM precipitates or settles out of the production stream and remains in the piping, separators, heater/treaters, and other production equipment. The produced water flows from the separators into storage tanks from which it is injected down disposal wells or recovery wells.



RAE-103341

Figure B.5-1. Typical production operation, showing separation of oil, gas, and water.

The NORM accumulated in production equipment scales typically contains radium coprecipitated in barium sulfate (BaSO_4). Sludges are dominated by silicates or carbonates, but also incorporate trace radium by coprecipitation. Ra-226 is generally present in scales and sludges in higher concentrations than Ra-228. The nominal activity ratio appears to be about three times as much Ra-226 as Ra-228. Typically, Ra-226 is in equilibrium with its decay products, but Ra-228 is not in equilibrium with its decay products. Reduced concentrations of Ra-228 daughters are due to the occurrence in the thorium series decay chain of two radium nuclides (Ra-228 and Ra-224) separated by Th-228 with a 1.9-year half-life. Thus radium mobilized from the formation initially becomes depleted in Ra-224 (half-life = 3.6 days) until more is generated by Ra-228 decay through Th-228.

For the sake of simplicity, the term radium is used in this section to refer to the combination of Ra-226 and Ra-228. Long-term radiological concern in waste disposal is dominated by the daughter products of Ra-226 rather than Ra-228 due to the much longer half-life of Ra-226 (1,600 years versus 5.75 years for Ra-228). Both are usually considered together in waste disposal decisions, however, since they are not distinguished by simple field measurements.

NORM radionuclides may also accumulate in gas plant equipment from Rn-222 (radon) gas decay, even though the gas is removed from its Ra-226 parent. The more mobile radon gas mostly originates in underground formations and becomes dissolved in the organic petroleum fractions in the gas plant. Once in surface equipment, it is partitioned mainly into the propane and ethane fractions by its solubility. Gas-plant deposits differ from oil production scales and sludges, typically consisting of an invisible plate-out of radon daughters on the interior surfaces of pipes, valves, and other gas plant equipment. These deposits accumulate from radon daughters at natural levels from the very large volumes of gas passing through the system. Since radon decays with a 3.8-day half-life, the only radionuclide remaining in gas plant equipment that affects its disposal is Pb-210, which has a 22-year half-life. Lead-210 decays by beta emission, with only low-intensity, low-energy gamma rays.

5.3.2 Oil and Gas Scale and Sludge Production Rates

The volume of NORM scale and sludge that is produced annually is uncertain, but recent estimates suggest that as many as one-third of domestic oil and gas wells may produce some radium-contaminated scale. It appears that the geological location of the oil reserve and the type of production operation strongly influences the prevalence of NORM accumulations. A review of surveys conducted in 13 states revealed that the number of facilities reporting NORM in production wells ranged from 90 percent in Mississippi to none or only a few in Colorado, South Dakota, and Wyoming (MCA88). However, 20 to 100 percent of the facilities in every state identified NORM in heater/treaters. A separate estimate based on Mississippi data indicates that one-half of the wells do produce NORM scale and ten percent of these have scale with elevated radium concentrations (BLI88).

An analysis performed in the U.K. estimated that a typical well of 10,000 feet with a 5.5-inch diameter pipe will produce 2 tons of scale per year for a well supplying 3,000 barrels of oil per day. In the U.K. oil producing area, there are approximately 850 production wells (compared to nearly 2 million wells in the U.S.). Based on this data, the U.K. estimated that their petroleum production wells would generate one thousand tons of scale per year (SCA88). Applying the relationship for the U.K. wells of 2 tons of scale per 3,000 barrels of oil to the U.S., which produces about 8.3 million barrels of oil per day (EIA88), the volume of scale produced in the U.S. is estimated to be about 6,000 MT per year.

For this report, a reference oil and gas production facility consisting of ten production wells is assumed, and the NORM waste associated with this facility is estimated from data developed by the American Petroleum Institute (API) and based on the results of laboratory and field work. The API has developed a database for oil and gas production wells throughout the U.S. and for equipment present at representative facilities. This database includes information on the estimated quantities of scale and sludge in production equipment derived from radiation measurements at facilities throughout the U.S. (API89).

Estimated quantities of scale and sludge for the representative 10-well production facility, based on observations and field measurements at several facilities, are shown in Table B.5-5. In defining the equipment, the API industry-wide survey headings were used. The typical facility is assumed to consist of ten production wells with an average life of 30

Table B.5-5. Equipment listing and characteristics of a 10-well production facility.^{a,b}

<u>Equipment Description</u>	<u>Unit</u>	<u>Total No. of Units</u>	<u>Gross Dimensions</u>	<u>Wall Thickness (Inches)</u>	<u>NORM Scale Thickness (Inches)</u>	<u>NORM Sludge Thickness (Inches)</u>	<u>Total Disposal Volume As Is (cu. ft.)</u>	<u>Scale Volume (cu. ft.)</u>	<u>Sludge Volume (cu. ft.)</u>	<u>Equipment Volume (cu. ft.)</u>
<u>Production Facilities</u>										
<u>Field Piping</u>										
Oil Line Piping	ft.	45,000	1" to 6" Dia. (4" NOM.)	0.38	0.08		15,395	1,227.74		5,652.00
Valves	ea.	25	1" to 6" Dia.	1.00	0.30		8	2.50		8.33
<u>Manifold</u>										
Headers/Manifolds	ea.	6	3" Dia. x 15'	0.30	0.10		5	0.50		1.78
Piping	ft.	300	3" Dia.	0.30	0.06		15	1.2		6.00
<u>Meter</u>										
Meters, Screens, Filters	ea.	6	2" Dia. x 2'	0.60	0.10		1			
<u>Pump</u>										
Oil Lease Pumps	ea.	2	5 hp (2' x 2' x 2')	1.00	0.10		16	0.20		2.00
<u>Sep</u>										
Test/Production Separators	ea.	2	3' Dia. x 10'	1.00	0.10	4.00	141	1.81	4.71	18.08
Free Water Knockouts (FWKO)	ea.	1	4' Dia. x 10'	0.60	0.10	2.00	130	1.25	2.09	7.50
Gun Barrel (Wash Tanks)	ea.	1	(400 bbl.) 12' Dia. x 20'	0.25	0.10	8.00	2,260	8.17	0.52	20.42
<u>Slank</u>										
Oil Stock Tanks	ea.	2	(500 bbl.) 15' Dia. x 20'	0.25	0.10	15.00	7,070	21.67	441.79	54.17
<u>VRU (Vapor Recovery Unit)</u>										
Suction Scrubbers	ea.	1	10" Dia. x 4'	1.00	0.10		314	2.33		23.33
<u>WINJ</u>										
Injection Wells	ft.	5,000	3" Tubing	0.25	0.10		1,000	131.00		327.50
Injection Pumps	ea.	1	(150 hp) 5' x 5' x 5'1	1.00	0.10		125	1.25		12.50
<u>Well and Well Head</u>										
Production Wells (Tubing)	ft.	13,800	2" Dia.	0.25	0.07		1,204	161.38		602.17
Christmas Trees	ea.	1	0	1.00	0.02		450	2.00		100.00
<u>H/T</u>										
Heater Treaters	ea.	1	4' x 25'	0.25	0.25	12.00	314	7.08	12.57	7.08
<u>Sump</u>										
Pig Traps	ea.	3	10" Dia. x 3'	0.50	0.10		5	0.25		1.25
Pits	ea.	3	(55 Gal) 22" Dia. x 3'	0.08	0.10	12.00	30	0.58	7.92	0.47

Table B.5-5. (continued)

<u>Equipment Description</u>	<u>Unit</u>	<u>Total No. of Units</u>	<u>Gross Dimensions</u>	<u>Wall Thickness (inches)</u>	<u>NORM Scale Thickness (inches)</u>	<u>NORM Sludge Thickness (inches)</u>	<u>Total Disposal Volume As Is (cu. ft.)</u>	<u>Scale Volume (cu. ft.)</u>	<u>Sludge Volume (cu. ft.)</u>	<u>Equipment Volume (cu. ft.)</u>
WLINE										
Water Lines	ft	1,000	2" to 4" Dia. (3")	0.30	1.00		2,000	283.33		79.00
Valves	ea.	8	2" to 4" Dia.	1.00	0.50		1	12.00		24.00
WTANK										
Water Storage Tanks	ea.	2	(400 bbls) 12' Dia. x 20	0.20	0.10	15.00	4,520	8.17	1.98	16.33
TOTAL							35,004	1,855	472	6,964

-
- a Waste volumes shown are volumes at the time the piping or tubing is replaced or the sludge is emptied from tanks and heater/treaters. Piping and tubing is replaced on average about every seven years. Sludge is emptied on average about every three years.
- b Table B.5-3 shows that there are approximately 620,000 producing wells in the United States. It is estimated that about 30 percent of these producing wells have equipment contaminated with NORM scale and sludge.

years. It is further assumed that tubing and some of the pipe in the wells will be replaced about every seven years giving a total of 3 replacements of the original tubing during the 30-year facility life. Sludge is assumed to be emptied from tanks and heater/treaters about every three years. Thus the quantities of NORM waste shown in Table B.5-5 only reflect short-term (i.e., less than 10 years) accumulations.

A review of Table B.5-5 indicates that the majority of the waste volume originates from the disposal of piping and valves, stock tanks, water storage tanks, wash tanks, and water lines and piping. Based on these values and the additional quantities of sludge generated during periodic cleaning of tanks, it is estimated that over 250 m³ (9,000 ft³) of scale and sludge are produced during a 30-year life cycle of the characteristic oil and gas production facility. It should be noted that it is difficult to translate the disposal volume into a weight because the waste volume is comprised of equipment characterized with large internal void spaces. In addition, the scale or sludge is trapped or internally coated in the equipment. Relatively speaking, the scale or sludge in such components usually makes up a small fraction of the total weight.

5.3.3 Oil and Gas Scale Handling and Disposal

In the past, when scale in oil and gas piping became a problem, the pipes were sent off-site to companies that would either clean out the scale or recycle the pipes. Pipes are cleaned by a process called rattling in which the scale is reamed out using a bit on a long shaft which is rotated inside the pipe. As the scale was not known to be radioactive it was stored on the ground at pipe cleaning yards or washed into the nearest pond or drainage basin (BAI88). Sludge from tanks was placed in pits or lagoons. Some piping containing scale was given to schools for use in playground equipment and as material for vocational welding classes (FUE88).

Because of concern that some of the contaminated pipes which were removed to nearby pipe cleaning facilities may have contaminated the environment, EPA's Eastern Environmental Radiation Facility conducted environmental radiological surveys. Their results showed some equipment and locations with external radiation levels above 2 mR/hr and soil contamination above 1,000 pCi/g of radium-226. Some contamination had been

washed into a nearby pond and drainage ditch at one site, as well as into an agricultural field with subsequent uptake of radium by vegetation (POR87).

Now that most companies in the petroleum industry are aware that pipe scale may be radioactive, pipes are usually measured for radioactivity. Piping and equipment containing NORM is generally being retained in controlled storage pending the promulgation of disposal regulations (CRC88, TDH89, DEQ89). Scale and sludge that is removed from piping and equipment is placed in drums and stored for later disposal.

Improper disposal of radioactive scale might lead to ground and surface water contamination, even though the scale is very insoluble. In addition, direct exposures can occur to individuals working or residing near the disposal site. Homes built over areas where scale has been disposed could have higher indoor radiation exposure levels and radon concentrations. There is probably little likelihood that radioactive scale would be used in building materials because of its physical properties. Since the yearly generation rates involve minimal volume of wastes, it is also unlikely that a commercial outlet would accept scale for incorporation in building materials.

The American Petroleum Institute (API) has recently sponsored a study to characterize accumulations of naturally-occurring radioactivity in oil field equipment, and to determine safe methods for their disposal. An analysis of disposal alternatives has been prepared (API90) which employs computer models to evaluate the risks from radiation exposures via seven different environmental pathways including radon inhalation, external gamma exposure, groundwater ingestion, surface water ingestion, dust inhalation, food ingestion, and skin beta exposure from NORM particles. Twelve waste disposal alternatives, ranging from landspreading to disposal in underground formations were evaluated. The disposal alternatives were evaluated in both humid and arid permeable geohydrological settings due to their differences in environmental transport of radioactivity. Analyses of a humid impermeable site were intermediate. Maximum NORM concentrations were computed corresponding to the greatest concentrations of NORM nuclides that could utilize a given disposal alternative without exceeding defined radiation exposure limits via a given exposure pathway.

5.3.4 Twenty-Year Oil and Gas Scale and Sludge Volume Estimates

For this assessment, the 20-year volume of NORM scale and sludge from oil and gas production equipment is estimated based on the number of crude oil producing wells shown in Table B.5-3 and the waste volume data characterizing a representative 10-well production facility shown in Table B.5-5. As described in Section 5.3.2, the representative facility consists of 10 production wells with an average life of 30 years. Piping and tubing is replaced about every seven years. Sludge is emptied from tanks and heater/treaters about every three years. Assuming that the NORM waste volumes shown in Table B.5-5 are volumes at the time piping is replaced or sludge is removed, the volume of NORM waste generated at the 10-well facility over a 20-year period is estimated to be about 250 m³ (9,000 ft³).

The total 20-year volume of NORM scale and sludge from all facilities in the U.S. is estimated on the assumption that the number of producing wells shown in Table B.5-3 (approximately 620,000 wells) will not change significantly during the next 20 years. Because U.S. oil production is based not only on U.S. demand but also on world-wide political and economic conditions, this assumption is subject to large uncertainties. The API-NORM database used to derive the waste volume information in Table B.5-5 was also applied to estimate the amount of equipment contaminated with scale and sludge from different oil producing regions. This was done by fitting the data to a log-normal distribution using the maximum and minimum measurements and the total number of measurements. It is estimated that about 30 percent of the producing wells in the U.S. contain equipment contaminated with NORM scale and sludge. The total volume of contaminated scale and sludge generated over a 20-year period is estimated to be about 4.6 million m³. The mass of this material is estimated to be 8.3 million MT, using a waste density of 1.8 MT/m³.

5.4 RADIOLOGICAL PROPERTIES OF OIL AND GAS SCALE AND SLUDGE

5.4.1 Radionuclide Concentrations

Naturally-occurring radioactive material (NORM) is present in the earth in varying concentrations in the geological formations from which oil and gas are extracted. Elevated NORM concentrations in oil and gas production equipment result when Ra-226 and Ra-228 and their decay products co-precipitate with mineral scales, such as BaSO_4 , that form deposits on the insides of field production equipment. Concentrations of NORM radionuclides in scale and sludge of petroleum production equipment can vary from essentially background (about 1 pCi/g) to tens of thousands of picocuries per gram. Factors which can affect the magnitudes of NORM concentrations in oil and gas production equipment include the location of the production facility, the type of equipment, how long the production well has been in operation, and changes in temperature and pressure that take place during extraction of the petroleum from the underground formation.

As discussed in Section 5.4.3, an American Petroleum Institute (API) industry-wide survey of radiation exposure levels of NORM in oil and gas production equipment (API89) showed a wide variation in NORM activity levels depending on the geographic origin of the equipment. The geographic areas with the highest equipment readings were northern Texas and the gulf coast crescent from southern Louisiana and Mississippi to the Florida panhandle. Very low levels of NORM activity were measured in equipment from California, Utah, Wyoming, Colorado, and northern Kansas.

The highest concentrations of radium appear to occur in the wellhead piping and in production piping near the wellhead. The concentration of radium deposited in separators is about a factor of ten less than that found in wellhead systems. There is a further reduction of up to an order of magnitude in radium concentration in heater/treaters and in sludge holding tanks. Concentrations of radium in scale deposited in production tubing near wellheads can range up to tens of thousands of picocuries per gram. The concentrations in more granular deposits, found in separators, range from one to about one thousand picocuries per gram. Higher concentrations are associated with hard scale deposits, apparently

associated with precipitation from the water phase. NORM concentrations in sludge deposits in heater/treaters and tanks are generally around 50 pCi/g.

The quantity and concentration of NORM waste in oil and gas production equipment also changes with time as the relative quantities of gas, oil, and water in the producing geological formation change. The trend is for the relative quantity of NORM to increase as the well ages and as gas and oil resources are depleted.

In addition to the previously cited API study (API89) which provides data on radiation exposure levels from NORM in petroleum production equipment, several other studies, both in the U.S. and in other countries, have been made to evaluate NORM concentrations in oil and gas scale. A British study of Ra-226 concentrations in oil and gas scale in production facilities in the United Kingdom revealed concentrations in scale ranging from 10 to over 100,000 pCi/g (MCA88). The highest radium concentrations were reported in downhole tubing and valves and ranged from 1,000 to 410,000 pCi/g. The measurements targeted scale with suspected elevated Ra-226 activities. Accordingly, these results probably represent a biased estimate of the Ra-226 concentration in scale.

One survey of U.S. facilities included the analysis (for Ra-226) of 125 scale samples collected from areas of elevated external gamma readings. The Ra-226 concentration in these samples ranged from 50 pCi/g to as high as 30,000 pCi/g, with an average of 5,484 pCi/g (MIL88). Since the study was done on scale with suspected high levels of radium, these concentrations probably also represent a biased estimate.

A survey of 25 facilities, performed by the E&P Forum, revealed Ra-226 concentrations ranging from less than 27 pCi/g to over 27,000 pCi/g (EPF87). Exxon Corporation has speculated that levels of 800 to 900 pCi/g may be common in the U.S., with some regional trending. Chevron speculates that levels of 20 to 25 pCi/g may be more common; however, tank bottoms may have concentrations as high as 100 pCi/g, and heater/treater units and separators may be characterized by scale with concentrations as high as 600 pCi/g (BLI88).

A more realistic estimate of the average Ra-226 concentration in oil and gas scale and sludge may be derived from 6,274 external gamma readings taken throughout several U.S. production facilities (SCA88). Based on these readings, and using a conversion factor of 1 to

5 pCi/g per μ R/hr above background (MIL87), the following distribution of Ra-226 concentrations in production equipment were estimated:

Median:	6 pCi/g
Average:	125 pCi/g
90 percentile:	250 pCi/g
99 percentile:	2,615 pCi/g
Maximum:	37,500 pCi/g

In view of the wide distribution of the reported data, it is difficult to define a generic set of radionuclide concentrations. It is also believed that the reported data favor equipment with elevated concentrations, while those that are low are often ignored or not reported. For the purpose of this report, the nominal concentration of radium in oil and gas scale is estimated using an approach with the following assumptions:

- The amount of scale and sludge in equipment of the generic facility is as shown in Table B.5-5.
- Average radiation exposure rates for specific types of equipment are taken from the API data base.
- Conversion of external gamma exposure rates to radium concentrations in different types of equipment are based on a conversion of 1 to 5 pCi/g per μ R/hr above background.

Since the instrument response for Ra-226 and Ra-228 and their decay products is similar, the estimated concentration is based on total radium. The weighted radium concentration, in scale and sludge from oil and gas production equipment, is estimated to be 210 pCi/g. The Ra-226 and Ra-228 concentrations are 155 pCi/g and 55 pCi/g, respectively. The weighting factor includes the presence of different amounts of scale and sludge in equipment (see Table B.5-5) and the relative measurements on the different types of equipment. It is assumed that the decay products of radium are in equilibrium. In summary, the radionuclides and their respective concentrations used in this assessment are as follows:

Radionuclide	Concentration (pCi/g)
Po-210	155
Pb-210	155
Ra-226	155
Th-228	55
Ra-228	55
Th-230	--
Th-232	--
U-234	--
U-235	--
U-238	--

5.4.2 Radon Flux Rates

No readily available information was found characterizing radon emanation rates from oil and gas scale waste. As was discussed earlier, it is difficult to characterize radon emanation or flux and disposal or storage methods. For example, particle grain size and the thickness of the scale deposits may govern the radon emanation rates. Similarly, the presence of oil or other petroleum products associated with the scale or sludge may reduce radon flux rates. Finally, since much of this waste is held within equipment (internally deposited), it may be difficult or even impractical to characterize radon emanation rates from internal surfaces. As was noted earlier, the presence and concentration of Ra-226 will govern radon emanation and diffusion properties from scale and sludge. For the purpose of this report, it is assumed that a radon emanation coefficient 0.1 would best characterize oil and gas scale and sludge waste (RAE88). This is somewhat lower than background radon emanation coefficients which are known to vary from about 0.2 to 0.4 in soils (NCR87).

5.4.3 External Radiation Exposures Rates

The results of a statistical evaluation of the exposure level data from the API industry-wide survey (API89) are shown in Table B.5-6. The table shows the results on a national basis in terms of difference over background by facility and type of equipment. The abbreviations used to specify equipment type are shown in Table B.5-7.

Table B.5-6.

Statistical analysis of radiation exposure levels associated with NORM in oil production and gas processing equipment -- national summary. (Source: API89)

Equipment	Number of Observations	Number of Observations Above Background	Difference Above Background ($\mu\text{rem/hr}$)				
			Minimum	25th Percentile	Median	75th Percentile	Maximum
<u>Oil Production Facilities</u>							
WOTHER	24	5	1.2	1.8	2.0	3.75	5.5
WPROD	2324	777	0.1	1.0	2.3	7.9	1487.0
METER	306	72	1.0	1.0	3.0	5.75	92.0
PUMP	1393	424	0.1	1.0	3.0	14.0	986.0
OTHER	2397	1007	0.1	1.0	4.0	15.0	3785.0
STANK	7005	2696	0.1	2.0	4.0	14.0	2475.0
MANIFOLD	2537	895	0.1	1.0	6.0	55.0	2995.0
SUMP	454	253	0.1	3.0	7.0	26.5	793.0
SEP	7887	3816	0.1	2.0	7.8	40.0	4491.0
H/T	2962	1495	0.1	2.0	8.0	47.0	3490.0
WTANK	3431	2140	0.1	3.0	8.0	35.0	3786.0
VRU	115	25	0.2	2.0	17.0	207.5	1287.0
WINJ	102	50	1.0	4.0	20.0	56.25	886.0
WLINE	341	176	0.2	6.0	34.6	100.0	2790.0
FLINE	1748	419	0.1	7.0	42.0	112.0	2991.0
<u>Gas Producing Facilities</u>							
COMPRESSOR	648	119	0.3	1.0	2.0	3.0	490.0
DEHYDRATOR	244	72	0.3	1.35	3.0	6.65	529.0
SWEETENER	234	30	0.2	1.0	3.45	19.5	220.5
INLET SCRUB	593	156	0.1	1.0	5.0	19.0	701.0
METER	101	32	0.3	1.15	5.5	51.0	695.0
CRYO UNIT	50	20	1.0	2.0	6.0	21.9	2985.0
OTANK	423	140	0.2	2.0	6.0	30.0	383.0
OTHER	430	165	0.3	2.9	7.0	23.0	995.0
FRAC TOWER	272	123	0.2	1.5	9.5	33.2	395.0
REFRIGER	143	56	0.1	2.0	16.0	68.75	595.0
BOTTOMS PUMP	40	30	0.5	3.0	17.0	45.25	220.0
PTANK	124	90	0.5	7.3	25.0	65.75	680.0
OPUMP	232	114	0.4	6.8	27.75	96.25	1391.0
PPUMP	71	53	0.1	9.5	31.0	97.5	1041.0

Table B.5-6. (continued)

<u>Equipment</u>	<u>Number of Observations</u>	<u>Number of Observations Above Background</u>	<u>Difference Above Background (ppm/hr)</u>				
			<u>Minimum</u>	<u>25th Percentile</u>	<u>Median</u>	<u>75th Percentile</u>	<u>Maximum</u>
PROD LINE	146	82	0.1	13.75	35.0	110.5	1080.0
PUMP	3	2	3.0	3.0	38.0	73.0	73.0
REFLUX PUMP	110	95	0.2	15.8	76.0	291.0	2985.0
Background				5.0	7.0	9.0	

Table B.5-7. Abbreviations used to designate equipment types in oil production and gas processing facilities.

<u>Abbreviation</u>	<u>Description</u>
<u>Oil Production Equipment</u>	
FLINE	Flow lines to include all valves and elbows
H/T	Heater treater
MANIFOLD	Manifold/header piping, valves, chokes, etc.
OTHER	All other measurements on service equipment
PUMP	All pumps
SEP	Separators of all types
STANK	Stock tanks
SUMP	Sumps to include pits, pigtraps, ponds, etc.
VRU	Vapor recovery units
WINJ	Injection wellhead
WOTHER	Other wellheads except injection and production wellheads
WPROD	Production wellhead
WLINE	Water lines to include all valves and elbows
WTANK	Water tanks
<u>Gas Processing Equipment</u>	
BOTTOMS PUMP	Pumps transferring liquids from the bottoms of towers
COMPRESSOR	Compressors and associated equipment
CRYO UNIT	All cryogenic process equipment
DEHYDRATOR	Dehydration equipment to include Glycol, EG, TEC systems, etc.
FRAC TOWER	All process towers and columns
INLET SCRUB	Inlet scrubbers, separators, etc.
METER	All metering equipment to include meters, meter runs, strainers, etc.
OPUMP	All other pumps
OTANK	All other tanks

Table B.5-7. (continued)

Abbreviation	Description
OTHER	All other gas processing equipment
PPUMP	Propane pump
PTANK	Propane tank
PROD LINE	All product lines
REFLUX PUMP	All reflux pumps
REFRIGER	All propane refrigeration system equipment
SWEETENER	All gas sweetening equipment

These exposure level data represent the most comprehensive and consistent set of NORM data available for petroleum operations. However, much of the data were collected at sites suspected of exhibiting some degree of radioactivity. The data were not collected in a statistically designed sampling plan. The number of observations from oil and gas equipment for a given geographic area may not be proportional to the actual amount of operational equipment in that area. Hence, the data may not be typical of a randomly chosen site and may tend to overstate the magnitude of the NORM occurrence.

NORM activity levels showed wide variability, both geographically and between items of equipment in the same geographic area. Approximately 64 percent of the gas producing equipment and 57 percent of the oil production equipment surveyed showed "zero" activity values relative to background. The geographic areas with the highest equipment readings are the entire gulf coast crescent (Brownsville, Texas to the Florida panhandle), northeast Texas, southeast Illinois, and a few counties in southern Kansas. The eastern gulf coast from Mississippi to the Florida panhandle had the highest consistent NORM activity levels surveyed in the entire United States.

NORM activity levels tend to be highest in specific types of equipment. Oil production equipment with the highest NORM activity levels is typically the water handling equipment. Median exposure levels for this equipment were measured to be in the 30 μ rem/hr to 40 μ rem/hr range (about 5 times background). Gas processing equipment with the highest levels includes the reflux pumps, propane pumps and tanks, other pumps, and product lines. Median radiation exposure levels for this equipment were measured to be in the 30 μ rem/hr to 70 μ rem/hr range. For both oil production and gas processing equipment, a few measurements were made of radiation exposure levels in excess of 1 mrem/hr.

5.5 SUMMARY OF OIL AND GAS NORM SECTOR

5.5.1 Generic Oil and Gas Scale Disposal Site

The generic oil and gas scale site is assumed to be located in the state of Texas. The state of Texas is known to have the highest number of oil and gas production wells. Although much of the oil and gas production equipment containing NORM is presently stored in controlled areas, some companies are now cleaning the equipment and proposing to dispose of the NORM at disposal sites. Therefore, the risk assessment for this sector is based on the disposal of oil and gas scale, and sludge waste at a disposal site. It is assumed that there are six (6) regional disposal facilities, based on the volumes of waste and wide distribution of the oil and gas production industry. The regional disposal facility is assumed to contain 767,000 cubic meters of such wastes. The facility is assumed to have a designated waste disposal area of 160,000 square meters, with a depth of 4.8 m. It is also assumed that the site is located near surface stream and that the region is underlain by an aquifer.

5.5.2 Population Exposure

The population density near and around the site is assumed to be the average for the state of Texas, at 64 persons per square mile (BOC87).

5.5.3 Radionuclide Concentrations

Elevated concentrations of uranium and thorium and their radioactive daughter products are often present in petroleum bearing geological formations. The uranium and thorium are highly insoluble and, as oil and gas are brought to the surface, remain mostly in place in the underground reservoir. However, radium is slightly soluble and may be transported with liquid phases to the surface where it is deposited with scale and sludge on the inside surfaces of oil and gas production piping and equipment. The concentration of radium in scale and sludge depends on its concentration in the underground petroleum

formation, on the physical and chemical characteristics of the formation, and on changes in temperature and pressure as the liquid phase is brought to the surface.

The highest concentrations of radium are typically found in hard scale deposits that form on the interiors of pipes and valves. The radium concentration in the scale is associated with the direct precipitation of minerals from the liquid phase and can range up to several thousand picocuries per gram of scale material. Median concentrations in scale are much lower, in the range of tens or hundreds of picocuries per gram. Radium concentrations in granular deposits and sludge are also much lower than concentrations in pipe scale. For the purpose of this assessment, an average total radium concentration of 210 pCi/g is assumed (155 pCi/g for Ra-226 and 55 pCi/g for Ra-228).

B.5 REFERENCES

- API90 Management and Disposal Alternatives for NORM Wastes in Oil Production and Gas Plant Equipment, RAE-8837/2-2, prepared by Rogers and Associates Engineering Corporation for American Petroleum Institute, May 1990.
- API89 Otto, G.H., A National Survey on Naturally Occurring Radioactive Materials (NORM) in Petroleum Producing and Gas Processing Facilities, American Petroleum Institute, Dallas, Texas, July 1989.
- API87 Measurement Protocol for the Occurrence of LSA Material, American Petroleum Institute, Dallas, Texas, March 1987.
- BAI88 Bailey, E., Texas Department of Health, Austin, TX, telephone conversation, March 10, 1988.
- BEL60 Bell, K.G., 1960, Uranium and Other Trace Elements in Petroleum and Rock Asphalts, U.S. Geological Survey, Professional Paper 356-B.
- BLI88 Bliss, W.A., (EPA, Las Vegas) Memorandum to Mr. M. Mardis, (EPA, Washington, D.C.), February 3, 1988.
- BOC87 Bureau of Census, Statistical Abstract of the United States - 1988, 108th Edition, Department of Commerce, Washington, D.C. 1987.
- CPD87 Conference of Radiation Control Program Directors, Regulation and Licensing of Naturally Occurring Radioactive Material, Part N of SSRCR, Draft 5, May 1987.
- CRC88 Conference of Radiation Control Program Directors, Regulation and Licensing of Naturally Occurring Radioactive Materials (NORM), June 6, 1988, Frankfort, KY.
- DEQ89 Louisiana Department of Environmental Quality, Regulation and Licensing of Naturally Occurring Radioactive Materials (NORM), Title 33, Part XV, Nuclear Energy, Adoption of Permanent Rule for NORM, September 20, 1989, Baton Rouge, LA.
- EIA88 Energy Information Agency, Petroleum Marketing Annual - 1987, Department of Energy, DOE/EIA-0487(87), Washington, D.C., October 1988.
- EPF87 E&P Forum, Low Specific Activity Scale Origin, Treatment and Disposal E&P Forum, U.K., London Report No. 6 March 1987.
- FUE88 Fuentes, E.S., State Department of Health, Jackson, MI, telephone conversation, February 19, 1988.

- JOH73** Johnson, R.H., D.E. Bernhardt, N.S. Nelson, H.W. Calley, Assessment of Potential Radiological Health Effects from Radon in Natural Gas, Environmental Protection Agency, EPA 520/1-73-004, Washington, D.C., 1973.
- NCR87** National Council on Radiation Protection and Measurements, Exposure of the Population in the United States and Canada from Natural Background Radiation, Report No. 94, Bethesda, MD, December 1987.
- MAR87** Martin, J.C., Regulation and Licensing of Naturally Occurring Radioactive Materials (NORM) in Oil and Gas Exploration and Producing Activities, Proceedings of Conference of Radiation Control Program Directors Annual Meeting, Boise, Idaho, May 21, 1987, American Petroleum Institute, Dallas, Texas, June 1987.
- MCA88** McArthur, A., Development and Operation of a NORM Processing and Disposal Facility for the U.S. Oil and Gas Industry, published in CRCPD Publication 88-2, 19th Annual National Conference on Radiation Control, May 18-21, 1987, Boise, Idaho, Conference of Radiation Control Program Directors, Frankfort, KY, 1988.
- MIL88** Miller, H.T., Disposition of Naturally-Occurring Radioactive Material in Crude Oil Production Equipment, Chevron Corp., San Francisco, CA, presented at the Annual Meeting of the Health Physics Society, Boston, MA, July 4-8, 1988.
- MIL87** Miller, H.T., Radiation Exposures in Crude Oil Production Chevron Corp., San Francisco, CA, presented at the Annual Meeting of the Health Physics Society, July 5-9, 1987, Salt Lake City, Utah.
- PET88** Petroleum Independent, published by Petroleum Independent Publishers, Inc., Washington, D.C. September 1988.
- PIE55** Pierce, A.P., J.W. Mytton, and G.B. Gott, Radioactive Elements and Their Daughter Products in the Texas Panhandle and Other Oil and Gas Fields in the United States, Geology of Uranium and Thorium, International Conference, 1955.
- POR87** Porter, C.R., (EPA, EERFL), letter to Mr. E.S. Fuentes, State Department of Health, Jackson, MI, January, 1987.
- RAE88** Safety Analysis for the Disposal of Naturally-Occurring Radioactive Materials in Texas, Rogers and Associates Engineering Corporation report to the Texas Low-Level Radioactive Waste Disposal Authority, Report RAE-8818-1, Salt Lake City, Utah, October 1988.
- SCA88** SC&A, Inc., Technical Supplements for the Preliminary Risk Assessment of Diffuse NORM wastes - Phase I, prepared by SC&A, Inc. for the Environmental Protection Agency, under contract No. 68-02-4375, October 1988.

- TDH89** **Texas Department of Health, Naturally-Occurring Radioactive Material in Pipe Scale, Interim Policy, Austin, TX, August 9, 1989, Draft.**
- UK85** **Guidelines for Operators on Naturally Occurring Radioactive Substances on Offshore Installations, U.K. Offshore Operators Association Limited, Series No. 5, July 1985.**

B.6 WATER TREATMENT SLUDGES

6.1 INTRODUCTION

Using 1985 water consumption rates, typically 400 billion gallons per day were withdrawn for use in land irrigation, distribution in public supply systems, industrial applications, and electric power generation (BOC87). About 40 billion gallons per day were used in public water supply and distribution systems alone. Assuming a U.S. population of 241 million, the daily consumption rate per individual is nearly 170 gallons. Since water comes from streams, lakes, reservoirs, and aquifers, it contains varying levels of naturally-occurring radioactivity. Radioactivity is leached into ground or surface water since it is always in contact with uranium and thorium bearing geological deposits before being withdrawn. The predominant radionuclides found in water include radium, uranium, and radon, as well as their radioactive decay products.

For reasons of public health, water is generally treated to ensure its safety for public consumption. Water treatment includes passing the water through various types of filters and devices which rely on chemical processes to remove impurities and organisms. If water with elevated radioactivity is treated by such systems, there exists the possibility of generating potentially radioactive wastes even if the treatment system was not originally intended to remove radioactivity. Such wastes include filter sludges, ion-exchange resins, granular activated carbon, and reject water from filter backwash.

Many municipal and private supply systems process water containing elevated radionuclide concentrations, most commonly radium and uranium (GIL84). While some treatment plants apply processes directed at specifically removing certain radionuclides from water, radium is most commonly removed by cation-exchange resins and a lime-softening process (HAH88). As a result of these processes, sludge may contain elevated radionuclides concentrations, thereby creating a potential source of NORM wastes.

The purpose of this section is to characterize the concentration and inventory of naturally-occurring radionuclides in water treatment sludge and the methods used to dispose

of such sludge. The description also presents data and information on the types and volumes of sludge, physical properties, disposal requirements, and current and projected use of sludge in agricultural applications. These data are used in Chapter D of this report to assess potential radiation exposures to members of the general public and critical population group.

6.2 OVERVIEW OF WATER SUPPLY SYSTEMS

6.2.1 Areas of Elevated Water Radionuclide Concentrations

There are about 60,000 public water supply systems serving the entire population of the United States and about 47,700 rely on ground water sources (LON87, HES85, GIL84). More than 90 percent of the ground water supply and distribution systems serve less than 3,300 people (HES85). Since the majority of the municipal water supply systems in the United States rely on ground water sources, the presence and distribution of naturally occurring radionuclides in water have been the subject of several studies. The results of these studies have shown that certain regions of the U.S. have elevated concentrations of naturally-occurring radionuclides (LON87, COT83, COT84).

Variation in natural conditions within the host geological formation, such as ground water pH, redox potential, radionuclide solubility and half life, and water withdrawal rates, directly affects the amount and distribution of naturally-occurring radioactivity. Generally, geological formations characterized by the presence of igneous and metamorphic rocks and sandstone tend to result in higher ground water radioactivity (HES85).

The predominant radionuclides found in water include radium, uranium, and radon, as well as their radioactive decay products. For example, radium-226 concentration in surface water is known to vary from 0.01 to 1 pCi/L and from 0.5 to 25 pCi/L in ground water (HES85, REI85, LOW88). Occasionally, these radionuclides are found at elevated concentrations. For example, radium concentrations as high as 200 pCi/L have been reported, while in most instances the concentration is seldom above 50 pCi/L (HES85). Radium concentration in surface water is typically much lower than that of ground water, ranging

from 0.1 to 0.5 pCi/L (HES85). The Ra-226 population weighted average concentration in community drinking water supplies is estimated to range from 0.3 to 0.8 pCi/L for Ra-226. The results of the National Inorganics and Radionuclide Survey (NIRS) indicate a higher weighted average of 0.905 pCi/L (LON87). Five states were noted to have still higher average concentrations ranging from 1.27 to 5.29 pCi/L (LON87). These states are Georgia, Illinois, Minnesota, Missouri, and Wisconsin.

There is less definitive information and data on the presence of Ra-228 in ground water. Typically, Ra-228 concentration is noted as the ratio of Ra-228 to Ra-226 activity. The Ra-228 to Ra-226 ratio has been reported to vary from 0.2 to 5, but a ratio of 1.2 is generally thought to be representative of average conditions (EPA86a, HES85). The major reason for the higher Ra-228 concentration is that the average crustal thorium and uranium activity ratio is about 1.2 to 1.5. Natural geochemistry enrichment or depletion processes may either increase or decrease this ratio. Accordingly, the Ra-228 ground water concentration is, on the average, believed to be slightly higher than Ra-226. The Ra-228 to Ra-226 ratio of 1.2 is also believed to characterize the distribution of these two radionuclides in surface waters (HES85). The Ra-228 population weighted average concentration in community drinking water supplies is estimated to range from 0.4 to 1.0 pCi/L (HES85, EPA86a). The results of the NIRS survey indicate a higher weighted average concentration of 1.41 pCi/L. Three states were noted to have higher averages ranging from 1.82 to 4.24 pCi/L (LON87), these states are Illinois, Minnesota, and Wisconsin.

Uranium is known to be present in both surface and ground water sources. Natural uranium is comprised of U-238 (99.27 percent natural abundance), U-235 (0.72 percent), and U-234 (0.006 percent). Uranium activity as high as 652 pCi/L was observed in both surface and ground water samples with a few supply systems exceeding 50 pCi/L (EPA86a, COT83). The average uranium concentrations in surface and ground water are believed to be about 1 and 3 pCi/L, respectively (COT83). The isotopic ratio of U-234 to U-238 is known to vary, with notably higher concentrations of U-234 in both surface and ground waters. The higher U-234 concentration is due to the alpha recoil process which enhances the mobilization and solubility of the decay product (U-234) when compared to the parent (U-238). Ratios as high as 28 have been noted, but most often the ratios are found within a narrower range of 1 to 3 (HES85). The population weighted average uranium concentration in community drinking water supplies is estimated to range from 0.3 to 2.0 pCi/L (HES85, EPA86a).

The presence of radon in ground water is known to vary significantly, sometimes over six orders of magnitude that of Ra-226. The geometric mean of ground water radon concentration is nearly 1,000 pCi/L (HES85, LOW88). For radon, the population weighted average is believed to range from 194 to 780 pCi/L (LON87, COT87).

In geological terms, the United States may be divided into 11 regions. Based on the results of an extensive water sampling and analyses program, two such regions, the North Central and the Coastal Plain, have been identified with elevated radionuclide (primarily Ra-226 and Ra-228) concentrations in drinking water supplies (COT83, COT84, HES85, LOW88). The results of this study indicate that elevated radionuclide concentrations above 5 pCi/L were most often (75 percent of the instances) noted in two regions, the Piedmont and Coastal Plain Provinces and North Central Region. The 5 pCi/L guideline for the combined presence of Ra-226 and Ra-228 has been established by the EPA for drinking water under the Safe Drinking Water Act (EPA76). By focusing on geological formations and aquifers with elevated radionuclide concentrations, it is possible to identify regions which would result in the production of significant volumes of water treatment sludge.

North Central Region - The North Central Region contains portions of Illinois, Iowa, Minnesota, Missouri, and Wisconsin. It is estimated that there are 355 public water supply systems in this region exceeding 5 pCi/L for both Ra-226 and Ra-228 (HES85).

Piedmont and Coastal Plain Provinces - The Piedmont and Coastal Plain Provinces include portions of New Jersey, North Carolina, South Carolina, and Georgia. It is estimated that about 200 public water supply system in this region exceed the 5 pCi/L, as defined above (HES85).

Other Areas - Other areas reported to have radium concentrations in excess of 5 pCi/L include portions of Arizona, New Mexico, Texas, Mississippi, Florida, and Massachusetts. The distribution of groundwater sources containing elevated levels of naturally- occurring radionuclides tend to be located in regional clusters, dependent on the presence of smaller geological formations. The estimated number of public water supply systems exceeding 5 pCi/L is approximately 80 (HES85).

It has been estimated that at least 500 water supply systems are known or suspected to exceed the 5 pCi/L concentration guidelines (EPA86a, HES85). For the regions and areas characterized above, it is estimated that 635 systems exceed the EPA limit. It is also suspected that there might be some undetected systems which have elevated water concentrations (HES85). For the purpose of this report, it is assumed that about 10 percent, or 64 systems, have yet to be identified. Accordingly, it is assumed that 699 (rounded off to 700) water supply systems exceed the EPA concentration standards.

6.2.2 Water Treatment Technology

A summary of the number and size of public water supply systems is presented in Table B.6-1 for the United States (EPA86b). Many of these systems employ a variety of water treatment processes to improve water quality. Undesirable tastes and odors are removed by aeration. Bacteria are destroyed by the addition of a few ppm of chlorine and excessive hardness is reduced by the use of ion-exchange resins and lime. Table B.6-2 presents a summary of water treatment systems which have been found to be effective in removing radioactivity (EPA88).

Lime softening is used on larger supply systems to soften water by the addition of calcium hydroxide. The calcium hydroxide raises the pH which causes the calcium and magnesium to precipitate. The precipitate, along with suspended solids, are removed by sedimentation and filtration. During this process, 80 percent to 90 percent of the radium in the water is also removed (HAH88). This process typically produces about 4 cubic yards (3.1 m³) of dewatered sludge per million gallons of processed water. Prior to dewatering, the sludge is about 2 to 5 percent solids. After dewatering, the sludge is about 50 percent solids (EPA86b, PAR88).

Ion-exchange resins are used on smaller water supply systems to soften water by replacing Ca and Mg ions with Na ions. In the process, about 95 percent of the radium is also removed (HAH88). However, the resins are usually backwashed for reuse rather than being disposed. The backwash water, which contains the radium, is typically discharged to storm sewers, underground injection wells or septic tanks, or is backwashed to another ion-exchange column for the selective removal of radium. As can be noted, wastes from water

**Table B.6-1 Numbers of public water systems and populations served
by sources and size category.^(a)**

System Category	Population per System (000)	<u>Surface Water</u>		<u>Ground Water</u>	
		Total Pop. (000)	No. of Systems	Total Pop. (000)	No. of Systems
1	25-100	243	4,596	5,020	130,091
2	101-500	880	3,544	11,424	48,004
3	501-1K	1,506	1,770	12,118	14,599
4	1K-3.3K	4,673	2,425	12,836	7,119
5	3.3K-10K	10,628	1,841	15,517	2,801
6	10K-25K	12,697	879	13,684	891
7	25K-50K	16,086	500	10,090	313
8	50K-75K	10,310	220	5,566	92
9	75K-100K	10,254	139	1,720	21
10	>100K	89,960	278	12,552	60
	Total:	157,281	16,192	101,427	203,991

(a) From Regulatory Impact Analysis for Drinking Water Regulations, EPA Office of Drinking Water (EPA86a).

Table I .6-2. Summary of treatment technologies for removal of naturally-occurring radionuclides from water.^(a)

Treatment Technology	Contaminant Removed	Removal Efficiency	Wastes Produced
Cation exchange	Radium	85-97%	Rinse & backwash water, brine regenerant solution (50-3, 500 pCi/L Ra)
Anion exchange	Uranium	95%	Rinse & backwash water, brine regenerant solution (25 mg/L U)
Lime softening	Radium Uranium	90% 85-90% ^(b)	Sludge from tanks (6-9 pCi/g Ra; 1-10 pCi/g U), filter backwash (6-50 pCi/L Ra), supernate (21-24 pCi/L Ra) from settling or concentrating sludge & filter backwash
Reverse osmosis	Radium Uranium	90% ---	Reject water (7-38 pCi/L Ra)
Electro-dialysis	Radium Uranium	90% ---	Reject water
Greensand	Radium	56% ^(c)	Solids & supernate from filtration backwash (21-106 pCi/L Ra)
Coprecipitation with BaSO ₄	Radium	95%	Sludge from tanks, filter backwash, supernate from settling or concentrating sludge & filter backwash
Selective sorbents	Radium	90+%	Selective sorbent with high levels of radium (110,000 pCi/g)
Activated alumina	Uranium	90+%	Rinse & backwash water, regenerant solution
Granular activated carbon	Radon Uranium Radium	96% --- ---	Granular activated containing radon decay products, uranium, & possibly radium
Aeration	Radon	95%	Radon released to air

(a) Data extracted from EPA82, EPA86b, and REI85.

(b) May be increased to 99% by the presence or addition of magnesium carbonate to the water.

(c) May be increased to 90% by passing the water through a detention tank after the addition of potassium permanganate prior to filtration.

treatment systems may contain elevated radionuclide concentrations, at times exceeding 2,000 pCi/g for Ra-226.

The other systems (such as reverse osmosis) listed in Table B.6-2 are either not in widespread use or generate a liquid waste product rather than sludges. Systems designed specifically for the removal of radium are available but are currently not in widespread use. Other types of water treatment processes are also known to remove radioactivity, but these methods have not been widely evaluated. For example, flocculation and coagulation when combined with filtration are believed to be effective in removing radionuclides with higher valences (DYK86). Such systems are widely used and, consequently, there is a potential that significant quantities sludge may be generated by this treatment process.

Table B.6-3 presents a summary of water treatment systems most often used by 211 water utilities (AWA87). The results shown are based on a 1985 survey conducted by the American Water Works Association. A total of 184 utilities reported the use of 20 different water treatment techniques and noted that two or more treatment methods were typically used at the same time. Furthermore, 27 utilities (13 percent) reported using no treatment methods at all. Four types of treatment methods most often (85 percent) used, included chemical treatment, filtration, coagulation and flocculation (as one), and sedimentation. Among these treatment methods or systems, all but two are especially relevant to the NORM issue because they are widely used, generate sludge, and are known to remove radioactivity from water (HAH88, PAR88, REI85, SOR88, DYK86). The two remaining treatment methods, aeration and chemical treatment, generate little or no sludge at all (PAR89, LOW87).

6.3 WATER TREATMENT WASTE GENERATION

6.3.1 Water Treatment Waste Generation

As was noted earlier, there are many factors which govern how much waste a water utility may generate. The major factors include water quality, water use, and type of water treatment system. For the purpose of this assessment, waste or sludge generation rates will

**Table B.6-3. Distribution of water treatment systems reported in use
by 211 water utilities surveyed in 1985.^(a)**

<u>Type of System</u>	<u>Note</u>	<u>Cited Use</u>	<u>Percent of Total</u>
Chemical	1	253	40.9
Filtration	2	111	18.0
Coagulation and flocculation	---	86	13.9
Sedimentation	---	76	12.3
Lime and soda lime	---	34	5.5
Aeration and volatilization	3	33	5.3
Ion exchange and activated charcoal	4	25	4.1
	Total^(b):	618	100.0

- (a) Based on 184 utilities reporting the use of 20 water treatment techniques. A total of 27 utilities (13%) reported using no treatment methods at all. Information and data extracted from the 1985 Water Utility Operating Data (AWA87).
- (b) Utilities typically use several treatment methods at the same time, hence the total number of systems cited exceeds the total number of utilities responding to the survey.

Notes:

1. Includes ozone, chlorine, chlorine dioxide, chloramine, and fluoridation.
2. Consists of direct, slow and rapid sand, and pressurized filtration.
3. Conventional aeration for taste and odor and aeration for removal of volatile organic contaminants.
4. Includes ion-exchange softening, resin beds for organics, and granulated and pulverized activated charcoal for filtration and removal of organic contaminants.

be based on the results of two surveys conducted by the American Water Works Association (AWWA), which conducts periodic surveys of the largest water utilities.

A summary of the 1984 and 1985 surveys results are shown in Table B.6-4. The survey results for 1984 encompass 430 water utilities which served 104 million people (AWA87). The 1985 survey results reflect a more modest population of 11 million people and 211 utilities (AWA87). The water consumption rates per capita were nearly identical for both years, 176 and 163 gallons in 1984 and 1985, respectively. The total amount of water processed in each year was reported to be 25.3 billion m³ in 1984 and 2.4 billion m³ in 1985. The total amount of sludge generated between both years is expected to be different since only half as many utilities responded in the 1985 survey and only a fraction of those generated sludge. A breakdown is also given for six types of sludge disposal methods. As can be noted, the largest quantities of sludge are disposed in lagoons, landfills, and by land application. The last method listed as "Return to head of treatment plant/supply" is really not a disposal method, but rather a recycling method. Only the settling sludge is disposed of while the decanted water is recycled. The sludge content is about 3 percent by weight.

In general, the results show a degree of internal consistency between both survey even though the number of utilities surveyed in 1984 served about ten times as many people. The only exception being that, on the average, the amount of sludge generated per utility is different only by a factor of three rather than ten. The discrepancy may be due to a difference in the distribution of utilities surveyed in 1984 and 1985.

Within the context of this assessment, two parameters are thought to provide better indices to estimate, in the aggregate, the potential sludge generation rates for all utilities. These are: 1) the sludge generation rate per capita, and 2) sludge generated per unit volume of processed water. The average of both years is used, see Table B.6-4. It is assumed that the total U.S. population is 241 million and that water consumption by public supply systems is 55.2 billion m³ per year (BOC87). Given the above, the yearly sludge generation rates are estimated to be:

Based on sludge/capita:	13 kg	241 million	3.1 million MT
----------------------------	-------	-------------	----------------

Table B.6-4. Summary of water utilities operating characteristics for 1984 and 1985^(a)

Parameter	1984 Data	1985 Data
Utilities Surveyed Response (No./%):	600 430/72	600 211/35
Population Served:	104 million	11 million
Water Production (in billion m ³)		
Total:	25.3	2.4
Ground:	6.3	0.7
Surface:	16.8	1.4
Purchased:	2.2	0.3
Average water use per capita:	176 gal/day	163 gal/day
Sludge Disposal (in thousand MT)		
Sewer:	32	4.3
Lagoon:	180	100
3rd Party Landfill:	42	20
Utility Landfill:	100	20
Land Application:	100	13
Return to head of plant/supply:	550	2.5
Total:	1,100	160
No. of utilities producing sludge:	253	109
Calculated Parameters		
Sludge per capita:	11 Kg	15 Kg
Sludge per utility:	4,300 MT	1,500 MT
Sludge per unit of processed water:	44 g/m ³	67 g/m ³

(a) Parameters and data taken from the 1984 and 1985 Water Utility Operating Data (AWA86, AWA87). Numbers may not add up to total because of the rounding off process.

Based on sludge/m ³ of water processed:	56 g/m ³	55.2 billion m ³	3.1 million MT
--	---------------------	-----------------------------	----------------

These results indicate that about 3 million metric tons (MT) of sludge are generated yearly in the United States from all utilities. In attempting to cap the maximum yearly sludge generation rate from all sources, the higher values shown in Table B.6-4 are used instead. These are 15 Kg of sludge per capita and 67 g of sludge per m³ of processed water. Applying these new parameters indicates that, other things being equal, 3.7 million MT of sludge are produced yearly. Accordingly, the total amount of sludge which could be considered a potential NORM waste is probably much less than 3.7 million MT since not all utilities process water with elevated naturally-occurring radioactivity. As noted earlier, it was assumed that only 700 water utilities are suspected of generating NORM wastes.

6.3.2 Water Treatment Waste Disposal Methods

The AWWA 1984 survey results are used to characterize the sludge disposal practices of utilities in 29 selected states. The 29 states were chosen based on information which indicates that several utilities in such states are known or suspected to process water with elevated radionuclide concentrations. The selection of these states is based on a review of studies and surveys conducted by Longtin, Hess, and Cothorn (LOW88, LON87, HES85, COT83, and COT84). The states are identified in Table B.6-5. The sludge generation rates were taken from the 1984 AWWA survey since it captured a greater number of utilities than the one of 1985. The results are summarized in Table B.6-5.

A review of Table B.6-5 indicates that although 54 percent of the sludge that is returned to the head of the water treatment plant, only 3.5 percent of this amount is sludge that requires disposal. For the remaining methods, 42 percent of the sludge is disposed in lagoons, and 29 percent is disposed in utility and third party landfills. About 20 and 5 percent of the sludges are disposed, respectively, by application on agricultural land and into sewers. A total of 831,000 metric tons was generated by 183 utilities and 392,000 metric tons of sludge was disposed in the true sense. On the average, each state and utility disposed 13,500 and 2,140 metric tons, respectively.

Table B.6-5. Sludge disposal practices and quantities for 183 utilities in 29 selected states.^(a)

<u>Disposal Method^(b)</u>	<u>Quantity (MT)</u>	<u>Percent of Total</u>
Return to head of plant/supply ^(c)		
Total:	(452,000)	(54.5)
Sludge Only:	13,600	3.5
Lagoon:	163,000	41.6
Land Application:	80,000	20.4
Utility Landfill:	74,000	18.8
Third Party Landfill:	40,900	10.4
Sewer:	20,800	5.3
Total Amount:	831,000	100.0
Total Disposed:	392,300	---

CALCULATED DATA

	<u>Generation (MT)</u>	<u>Disposal (MT)</u>
Average per state:	29,000	13,500
Average per utility:	4,600	2,140

-
- (a) Data extracted from the 1984 Water Utility Operating Data (AWA86). Numbers are rounded off.
- (b) Data characterizing disposal practices of 183 utilities located in 29 states. The states include: AZ, CA, CO, CT, FL, GA, IL, IN, IO, KA, MA, MN, MI, MO, NB, NE, NH, NJ, NY, NC, OK, PA, SC, SD, TX, UT, WA, WI, and WY.
- (c) Only 2 to 5% of the total amount is actually sludge, the balance is decanted water. Three percent is assumed here in estimating the sludge volume destined for disposal.

Three methods are used to estimate the amount of sludge which may be categorized as a NORM waste. The first method simply assumes that all 700 utilities generate sludge at 2,140 MT per year. This yields a total yearly disposal rate of 1.5 million MT. This amount is believed to be too high since it represents 50 percent of the total amount of sludge generated by all sources. This estimate is also unrealistic since it assumes that all utilities generate NORM wastes regardless of the source of water and type of treatment systems.

In the second method, if one were to assume that the disposal rate per state (13,500 MT) is representative of overall practices, then the corresponding amount requiring disposal is nearly 400,000 MT, based on the 29 selected states. This amount of sludge is lower, but is also too high since it assumes that all utilities generate NORM wastes regardless of the source of water and type of treatment systems.

The third approach involves using the average water utility sludge generation rate based on the 1984 survey data and adjusting it to reflect specific factors which characterize this NORM sector. The average sludge generation rate is adjusted for the fact that: 1) about 80 percent of the water supply systems rely on ground water, 2) about 90 percent of the users do not need finished or potable water, and 3) that about 28 percent of the utilities use water treatment systems which may remove naturally-occurring radioactivity. It is assumed that such treatment systems include filtration (18 percent), lime and soda lime (6 percent), and ion-exchange and activated charcoal (4 percent) (see Table B.6-3 for details). An overall removal efficiency of 85 percent is assumed for these systems based on the data given in Table B.6-2. An average sludge generation rate of 2,140 MT was previously estimated, see Table B.6-5. Accordingly, it is estimated that, on the average, about 314 MT of sludge and 52 MT of spent resin and charcoal beds will be generated yearly by such a utility. Since it was assumed that there are 700 suspect water utilities in the continental U.S., the total yearly NORM waste generation is estimated to be 256,000 MT, which is rounded off to 260,000 MT.

In view of these broad assumptions, it can be noted that the total amount of sludge and spent resins and charcoals beds which may be classified as a NORM waste is perhaps on the order of 260,000 MT, and possibly less. The earlier estimate of 1.5 million metric tons is believed to be much too high since it does not reflect some of the important characteristics

of this NORM sector. As noted earlier, there are water treatment systems which have not been considered in this estimate, but which are believed to generate sludge as a potential NORM waste. For example, flocculation and coagulation when combined with filtration are thought to be an effective process to remove radionuclides of higher valences (DYK86). Such systems are widely used and, consequently, there is a potential that significant quantities of sludge may be generated by this treatment process. Finally, it is suspected that the characteristics of such NORM wastes, including spent resin and charcoal beds, fall within a spectrum ranging from wastes with very low to those with very high radionuclide concentrations.

Given that these estimates are based on data for a single year and lack any information characterizing disposal practices over longer time periods, this range is assumed to bracket the amounts of sludge which could be considered a potential NORM waste. It is also not clear from past survey data what is the total number of utilities which have passed the EPA drinking water standards for finished water, but still may result in the generation of water treatment sludges at concentrations which may still be of concern in the context of this assessment. Although the resulting radionuclide concentrations may be relatively low when compared to instances with elevated levels, however, it is most likely that such type of wastes are being generated in much larger quantities. For the purpose of this assessment, it is assumed that 260,000 metric tons of sludges and spent resins and charcoals are generated yearly by this NORM sector.

6.3.3 Utilization of Water Treatment wastes

About 20 percent of the total amount of sludge generated yearly is put into useful application, e.g., land spreading and injection into agricultural fields. Other disposal methods, which include the placement of sludge in landfills (29 percent) and in lagoons (42 percent), are not considered as utilization practices. It could, however, be argued, that given the nutrient properties of sludge it is conceivable that areas which were once disposal landfills or lagoons could be later used for agricultural production. Accordingly, this assessment considers both disposal into landfills and agricultural applications.

Potentially contaminated waste byproducts of drinking water treatment may include lime sludge, backflush water, spent ion-exchange media, and sand filter elements. Very little or only patch work regulatory guidance exists controlling the disposal of such NORM wastes. However, future disposal practices may rely to a greater extent on discharging backwash waters to lagoons or ponds. Such practices will result in the accumulation of radium in bottom sediments which may represent an additional source of NORM wastes. The ponds may have to be periodically dredged and the bottom sediments may require proper and permanent disposal.

Storm Sewer - Material discharged into a typical storm sewer is routed to a natural water body, in which sludge may accumulate in aquatic sediments depending upon the flow rate of the water body and addition of natural waters. Liquid effluent standards applicable to Nuclear Regulatory Commission (NRC) licensees have been established under Title 10, Part 20 of the Code of Federal Regulations (10 CFR 20):

$C_{\text{Ra-226}}^{30} + C_{\text{Ra-228}}^{30}$ are less than 1, where;

$C_{\text{Ra-226}}$ = concentration of soluble Ra-226 in the discharge water (pCi/L),
and

$C_{\text{Ra-228}}$ = concentration of soluble Ra-228 in the discharge water (pCi/L).

The radium concentrations can only be averaged over a period of one year (NRC88). State agencies adopting the federal standards have adopted the NRC limits (HAH88).

Sanitary Sewer - Sludge and other waste water residues discharged into sanitary sewer systems are ultimately treated at a sewage treatment plant. For releases into sanitary sewers, the NRC regulations include the following criteria under 10 CFR 20:

1. The material must be readily soluble or dispersible in water,
2. The quantity of radium released into the system by the licensee in one day does not exceed either:
 - a. The quantity which if diluted by the average daily quantity of sewage released into the sewer by the licensee, will result in an average concentration equal to 4×10^{-7} $\mu\text{Ci/mL}$ radium-226 and 8×10^{-7} $\mu\text{Ci/mL}$ radium-228, or

- b. 0.1 microcuries radium-226.
3. The quantity of radium released into the system by the licensee in any one month, if diluted by the average monthly quantity of water released by the licensee, will not result in an average concentration exceeding 4×10^{-7} $\mu\text{Ci/mL}$ radium-226 and 8×10^{-7} $\mu\text{Ci/mL}$ radium-228; and
 4. The gross quantity of licensed and other radioactive material, excluding carbon-14 and tritium, released into the sewerage system by the licensee does not exceed one curie per year.

The state of Wisconsin has implemented standards for sanitary sewer discharge in the form (WIS85):

$C_{\text{Ra-226}}^{400} + C_{\text{Ra-228}}^{800}$ are less than 1, where;

$C_{\text{Ra-226}}$ = concentration of soluble Ra-226 in the waste water (pCi/L), and

$C_{\text{Ra-228}}$ = concentration of soluble Ra-228 in the waste water (pCi/L).

The radium concentrations derived above may not be averaged over a period greater than one month. In addition the total amount of radionuclide discharge in one year must not exceed 1 curie. As mentioned for storm sewer discharge, state agencies adopting these standards for permitted facilities may enforce them.

Agricultural - Residual lime sludge from a water treatment plant is sometimes dewatered and provided to farmers for free or a nominal fee. The sludge is spread onto a field in a similar manner as other fertilizers, and tilled into the soil. Currently, only Wisconsin and Illinois have regulatory programs that require testing of sludges and fields prior to dispersal (HAH88, WIS88). Frequent application of sludges over an extended period of time, or stockpiling may create significant accumulations of radionuclides. Because of this concern, some states are imposing limits on the amounts of radioactivity which may be introduced in fields. For example, the state of Illinois authorizes the disposal of sludge in agricultural lands provided that the combined concentration of sludge and soil will not increase the Ra-226 soil concentration by more than 0.1 pCi/g (HAH88).

Landfill - The disposal of sludge at municipal landfills is not regulated by states other than Wisconsin and Illinois. At landfills, contaminated material is typically covered and

compacted on a daily basis. Disposal site design features, such as a clay lining or isolation from useable aquifers, limit the transport of radionuclides out of the landfill. Other features, such as compacted clay layers placed above radium-contaminated sludges reduce water infiltration and radon emissions. The radionuclides are, therefore, not likely to be available for movement into the environment unless radionuclide leaching and transport are enhanced by hydrogeological and meteorological conditions. Similarly, if former landfill sites were to be subsequently used for residential housing or commercial development, then that population could become exposed to higher radiation levels.

Deep-well Injection - Deep-well injection involves the pumping of sludge into a stable geologic formation. The stability and immobility of the injected waste are governed by parameters, such as the absence of fractures, minimal water infiltration, and chemical conditions which may alter the solubility of the radionuclides. Deep-well injection is not in common use and is specifically prohibited in Wisconsin and Illinois (H 488). The EPA also discourages this practice because of its potential detrimental impact on ground water aquifers.

Non-Sewered Disposal - Non-sewered disposal typically involves the disposal of waste water in private septic systems. Failure of these systems can lead to transport of contaminants through certain geologic media. However, the scale and environmental consequences are estimated to be minimal.

With the current information, it is not possible to characterize disposal practices and waste inventories among storm sewer, sanitary sewer, and unsewered releases, and those that involve deep-well injection. It is also recognized that for the other identified disposal practices there exists some uncertainty as to their representativeness on a national level. Given these varied disposal practices and information based on the survey results of a limited number of utilities, there exists a need to further characterize water treatment methods and disposal practices on a larger scale. Additional data correlating input water volumes to output waste concentrations would be useful in determining waste generation rates on a nationwide basis for a particular type of treatment process. The data would need to be based on a representative number of water treatment plants utilizing a specific treatment technique. Studies of actual disposal methods in use by water utilities are also needed to establish the basis to form population risk models. It is understood that the American Water Works

Association will initiate in late 1989 another survey of water utilities (AWA89). The survey will target the 1,000 largest water utility in the United States. The results of this survey should, in part, help resolve some of the questions raised above.

6.3.4 Twenty-Year Sludge Generation Estimates

For the purpose of estimating the 20-year inventory of NORM wastes, it is assumed that 260,000 metric tons of sludge are generated yearly (see above discussion for more details). The growth in water use is keyed primarily to population increase rather than other indices, such as economic growth. It is also recognized that other factors may influence water usage and the number and distribution of water utilities. For example, small water utilities may go out of business, but the service must continue since the demand and population remains. The service is usually taken over by a new or perhaps larger utility.

Similarly, as water demand increases, new demand may be placed on existing systems and a greater emphasis may be placed on recycling water rather than increasing water withdrawal rate from existing aquifers. A larger fraction of the water supply may also come from surface water bodies. Because of the presence of organic contaminants in surface streams and lakes, utilities may be forced to adopt improved water treatment technologies to meet more stringent regulatory requirements. The current water treatment technology may also improve over time such that new treatment systems would extract more impurities and generate more sludge. These factors would result in the generation of greater quantities of sludge than current rates. Within the context of this study, it is not possible to estimate the impact of improved technology and regulatory requirements on future waste generation rates. Given that the yearly generation rate is already based on an upper estimate, no further corrections are made other than for an increase in population growth.

The annual U.S. population growth rate has been estimated to decrease over the next 20 years; from 0.99 percent for the ten- year period ending in 1990, to 0.71 percent from 1990 to 2000, and finally to 0.57 percent beyond the turn of the century (BOC87). An average population growth rate of 0.76 percent is used here given these trends. Compounded over the next 20 years, the population growth factor is 1.16. Accordingly, the total 20-year inventory,

assuming a yearly sludge generation rate of 260,000 metric tons, is estimated to be 6 million metric tons.

6.4 RADIOLOGICAL PROPERTIES OF TREATMENT SLUDGE

6.4.1 Radionuclide Concentrations

As was noted earlier, the predominant radionuclides found in water include radium, uranium, and radon, as well as their radioactive decay products. For example, radium-226 concentration in surface water is known to vary from 0.01 to 1 pCi/L and from 0.5 to 25 pCi/L in ground water (LOW88, HES85, COT84, COT83, REI85). Occasionally, these radionuclides are found at still higher concentrations. For example, radium concentrations as high as 200 pCi/L have been reported, while in most instances the concentration is seldom above 50 pCi/L (HES85). States with large numbers of water treatment plants processing raw water in excess of 5 pCi/L are located in Illinois, Iowa, Missouri, Wisconsin, North Carolina, South Carolina, and Georgia (LON87, HES85, COT84, COT83).

In general, the concentration of radium in sludge will depend on water quality, the aquifer from which the water is withdrawn, water quality, water use, and the type of treatment systems. More specifically, the following major factors will govern the characteristics of sludge:

1. Presence of naturally-occurring radioactivity and radionuclide concentrations in the water supply,
2. Radionuclide removal efficiency for a given water treatment system, and
3. The amount of sludge produced per unit volume of water processed.

Assuming an overall average Ra-226 concentration of about 1 pCi/L, a radium removal efficiency of 90 percent, and a sludge generation rate of 3.1 m³ per million gallons of water treated (HAH88), the average concentration of Ra-226 in sludge is estimated to be about 1

pCi/g. Correcting for the fact that dewatered sludge is about 50 percent water, the average concentration of Ra-226 in dry sludge is about 2 pCi/g. This calculation yields a useful rule of thumb, that is, about 1 to 2 pCi/g sludge is produced per pCi/L of Ra-226 in the water supply. This estimate does compare favorably with measured values reported in the literature (EPA76, HAH88). For example:

<u>Location</u>	-- Ra-226 Concentration --	
	<u>Raw Water</u> (pCi/L)	<u>Lime Sludge</u> (pCi/g dry)
Elgin, IL	5.6	6.1
Peru, IL	5.8	9.0
Wisconsin	1.0-5.3	2.1-32.8

Using the above calculational approach, it is concluded that the average Ra-226 concentration in sludge is comparable to that in soil (NCR87). However, this conclusion is speculative and may need to be verified by a field survey and sampling program.

Although the average Ra-226 concentration in sludge is typically low, public water treatment facilities which process water supplies with elevated Ra-226 concentrations are expected to generate sludge with elevated levels of Ra-226. Based on data reported by states exceeding the 5 pCi/L standards, the combined radium concentrations were noted to range from 5 pCi/L to about 25 pCi/L, with an average of about 10 pCi/L (HES85). Since the ratio of Ra-228 to Ra-226 is about 1.2 (HES85), the average Ra-226 concentration in water supplies which exceed the current standards is about 4 pCi/L. Using the rule of thumb described above, sludge from these systems may be expected to contain an average Ra-226 concentration of 4 to 8 pCi/g.

Radium selective resins, on the other hand, do generate wastes at much higher concentrations, but in much smaller quantities. The radionuclide concentration in these wastes is dependent upon the type of resins used, the amount of regenerant used, and how frequently the resins are regenerated. The radionuclide concentration in resins and regeneration wastes are known to vary. Field data indicates that radium concentrations between 320 to 3,500 pCi/L were noted in the column rinse and brine. Average and peak concentrations of 23 and 158 pCi/L, respectively, have been noted in regenerant wastes (EPA88). Radium build-up in cation-exchange resins has been observed to average at about

9 pCi/g, with peak concentrations ranging from 25 to 40 pCi/g. Given the broad variability of ground and surface water concentrations, the uncertainty with the type and number of water treatment systems being used, and their effective radionuclide removal efficiency, a simple approach is used to estimate radionuclide concentration in sludge.

It has been shown that an approximate "rule of thumb" relationship for radium concentration in sludge is given by two times the influent radium concentration in water. Sludge concentrations of U-238, Th-230, Th-232, Th-228, and U-235 were calculated using this method, even though it has been shown that certain water treatment processes do not remove uranium as efficiently as radium (REI85, EPA86a). The Pb-210 and Po-210 sludge concentrations were estimated by assuming a radon emanation coefficient of 40 percent for moist sludge. The average sludge radionuclide concentration is as follows:

	<u>Influent Water - pCi/L</u>	<u>Resultant Sludge - pCi/g</u>
U-238 -	2.0	4.0
U-234 -	2.0	4.0
Th-230 -	0.1	0.2
Ra-226 -	8.0	16.0
Th-232 -	0.1	0.2
Ra-228 -	10.0	20.0
Th-228 -	0.1	0.2
U-235 -	0.014	0.03
Pb-210 -	4.8	10.0
Po-210 -	4.8	10.0

These influent concentrations represent radionuclide concentrations in excess of those experienced by most water treatment plants. The variation of influent radionuclide concentrations to the water treatment plant is based on solubility and chemical properties of certain elements in the ground water. Such properties include the relatively low solubilities of thorium ions, desorption of radium from certain geologic formations based on the ionic strength of the groundwater, and the transport of uranyl ions (GIL84, SOR88).

6.4.2 Radon Flux Rates

No readily available information was identified characterizing radon emanation rates from such wastes. Radon emanation rates from sludge (including spent resins and charcoal beds) are assumed to be nearly identical to that of typical soils. For example, the NCRP notes that for typical soils, an average radon emanation rate is about 0.5 pCi/m²-s per pCi/g (NCR87). For an assumed Ra-226 concentration of 16.0 pCi/g (see above), the corresponding radon flux rate is about 8 pCi/m²-s, other things being equal.

6.4.3 External Radiation Exposure Rates

Radiation exposure rates associated with the disposal of sludge are expected to be relatively low when compared to ambient background levels. For spent resin and charcoals beds, exposure rates may, however, be much higher. For example, exposure levels as high as several mR/h have been observed on charcoal and resin beds (LOW88). Depending upon the source of radioactivity (radium vs. radon and its decay products), the radiation levels may quickly decay with time. Given the disposal method and the mode of exposure, radionuclides, and source to receptor geometry, it can be assumed that the resulting radiation doses may be scaled up based on empirically derived exposure rate conversion factors for environmental conditions. The conversion factors represent exposure rates for typical soils and include the effects of gamma ray scatter, build-up, and self-absorption (NCR87). For example, the conversion factors for the uranium and thorium decay series are 1.82 and 2.82 μ R/h per pCi/g, respectively. Assuming a Ra-226 (for U-238) and Ra-228 (for Th-232) concentration of 16 and 20 pCi/g, respectively, the total incremental exposure rate is estimated to be about 86 μ R/h. The exposure rate would in fact be less since the decay series would not have had the time to achieve secular equilibrium. In the United States, ambient exposure rates due to terrestrial radiation are known to range from 3 to 16 μ R/h (NCR87).

6.5 GENERIC SITE PARAMETERS AND SECTOR SUMMARY

This section presents a summary of the data and parameters which are used to perform the risk assessment of this NORM sector. The radiological assessment model is described in Chapter D. This chapter also introduces parameters and assumptions which are both generic and specific to each NORM sector. This information is not presented nor repeated here.

6.5.1 Generic Water Treatment Site

The generic water treatment plant is assumed to be located in Illinois. This state has been shown to have consistently elevated concentrations of Ra-226 and Ra-228 in ground water (GIL84, HES85, LOI 87), it has a large agricultural base, and is more densely populated. Two scenarios are developed for this NORM sector: 1) agricultural uses of sludge, and 2) landfill disposal of sludge. Due to the limited information on non-sewer wastewater discharge and deep-well injection, these disposal pathways will not be addressed here for the purpose of this risk assessment. It is assumed that relatively few water treatment facilities dispose of sludge in this manner. Sanitary sewer sludge is typically treated at a wastewater treatment plant. Storm sewer disposal will not be discussed due to limited information about the practice and data characterizing the mobility and availability of radium in this kind of aquatic environment. For the purpose of this assessment, the two remaining options include agricultural application or landfill disposal.

Agricultural Use

Sludge is commonly applied or spread into agricultural fields using methods which are similar to those used for fertilizers. For sanitary reasons and to minimize surface water runoff, states typically recommend that the sludge be injected or plowed under at the time of application (WIS75, WIS84, WIS88). For the purpose of this assessment, it is assumed that the sludge is either plowed under or injected to a root zone depth of 15 cm. The sludge is assumed to be introduced over the entire acreage and applied at rate of about 4.5 tons per acre every other year for 20 years (WIS75). The model site for this scenario is assumed to be

an average Illinois farm of 340 acres (BOC87). It is assumed that the field is bordered on one side by a nearby stream and the region is underlain by an aquifer. The size of the field is assumed to be square with dimensions of 1,200 m by 1,200 m. Given the application rate and acreage, 1,390 MT of sludge is introduced during each application and a total of 13,900 MT is disposed over a 20-year period. These quantities are simply rounded off to 1,400 and 14,000 MT, respectively.

Municipal Landfill Disposal

This scenario addresses the disposal of radium contaminated sludge into a typical municipal landfill serving a large community. Since the water utility supplies water to a small community, the utility is assumed to be using a third-party landfill rather than its own. It is assumed that the landfill accepting the sludge is used for other purposes as well. A 12-inch cover material is placed over the sludge on a daily basis (WIS88). Since the landfill was opened some years ago, it is assumed that the no special requirements were imposed on the site regarding the installation of a leachate containment system. At closure, a 1 ft layer of topsoil is placed over the fill area. Credit is taken only for the surface layer of the soil cover. The landfill is assumed to be 40 acres (16 hectares). It is assumed that the field is bordered on one side by a nearby stream and the region is underlain by an aquifer. The size of the field is assumed to be square with dimensions of 400 m by 400 m. The sludges are disposed by a water treatment plant creating 366 MT of sludge per year, based on the earlier estimates. The total amount of sludge disposed over a 20-year time period is assumed to be 7,320 MT.

6.5.2 Population Exposure

The model site for this scenario is assumed to be located in a rural Illinois. The population density is assumed to be that of the state of Illinois, at 210 people per square mile (BOC87).

6.5.3 Radionuclide Concentrations

The presence of radium in sludge depends upon the initial water Ra-226 and Ra-228 concentrations. In regions where water supplies exhibit elevated radioactivity levels, sludge from water treatment systems are expected to have higher radionuclide concentrations. However, it has been shown that raw water with less than 5 pCi/L of total radium, when processed, may produce a significant accumulation of radium in sludge. Given the broad variability of ground and surface water concentrations, the uncertainty with the type and number of water treatment systems being used, and their effective radionuclide removal efficiency, a simple approach was used to estimate radionuclide concentration in sludge. A rule of thumb was applied with which to convert influent water concentration to resultant sludge concentration. The selected radionuclide concentrations (see Section 6.4.1) assumed that the water (and consequently the sludge) originates from areas which are traditionally high in naturally-occurring radioactivity.

B.6 REFERENCES

- AWA89 Telephone Communication with Mr. Kurt Keely, September 27, 1989, American Water Works Association, Denver, CO.
- AWA87 American Water Works Association, 1985 Water Utility Operations Data, Denver, CO, 1987.
- AWA86 American Water Works Association, 1984 Water Utility Operations Data, Denver, CO, 1986.
- BOC87 Department of Commerce, Statistical Abstract of the United States - 1988, 108th Edition, Bureau of Census, 1987.
- COT83 Cothorn, C.R., Lappenbusch, W.L., Occurrence of Uranium in Drinking Water in the U.S., Health Physics Journal, Vol. 45(1), July 1983.
- COT84 Cothorn, C.R., Lappenbusch, W.L., Compliance Data for the Occurrence of Radium and Gross Alpha-Particle Activity in Drinking Water Supplies in the United States, Health Physics Journal, Vol. 46(3), March 1984.
- DYK86 Dyksen, J.E., et al., The Capabilities of Standard Water Treatment Processes to Meet Revised Drinking Water Regulations, AWWA, Annual Conference Proceedings, June 22-26, 1986, pp. 951-965, Denver, CO.
- EPA76 Environmental Protection Agency, Determination of Radium Removal Efficiencies in Illinois Water Supply Treatment Processes, Illinois EPA prepared for the U.S. EPA, Office of Radiation Programs, May 1976.
- EPA82 Environmental Protection Agency, Disposal of Radium-Barium Sulfate Sludge From a Water Treatment Plant in Midland, South Dakota, Technical Assistance Program Report prepared by Fred C. Hart Associates, Inc. for the U.S. EPA, Region VIII, December 1982.
- EPA86a Environmental Protection Agency, 40 CFR 141 Water Pollution Control; National Primary Drinking Water Regulations; Radionuclides: Advance Notice of Proposed Rulemaking, Federal Register Notice, Vol. 51, No.189, September 20, 1986.
- EPA86b Environmental Protection Agency, Technology and Costs for Treatment and Disposal of Waste byproducts by Water Treatment for Removal of Inorganic and Radioactive Contaminants, September 1986.
- EPA88 Environmental Protection Agency, Suggested Guidelines for the Disposal of Naturally Occurring Radionuclides Generated by Drinking Water Plants, Waste Disposal Work Group, Office of Drinking Water, June 1988.

- GIL84** Gilkeson, R. H., et al., Isotopic Studies of the Natural Sources of Radium in Groundwater in Illinois, University of Illinois Water Resources Center, report UILU-WRC-84-183, prepared for the United States Department of the Interior, April 1984.
- HAH88** Hahn, N. A. Jr., Disposal of Radium Removed From Drinking Water, AWWA Journal, July 1988.
- HES85** Hess, C. T. et al., The Occurrence of Radioactivity in Public Water Supplies in the United States, Health Physics Journal, Vol. 48 (5), May 1985.
- LON87** Longtin, J.F., Radon, Radium, and Uranium Occurrence in Drinking Water from Groundwater Sources, AWWA Journal, June 14, 1987.
- LOW88** Lowry, J.D. and S. B. Lowry, Radionuclides in Drinking Water, AWWA Journal, July 1988.
- LOW87** Lowry, J.D. et al., Point of Entry Removal of Radon from Drinking Water, AWWA Journal, April 1987.
- NCR87** National Council on Radiation Protection and Measurements, Exposure to the Population in the United States and Canada from Natural Background Radiation, NCRP Report No. 94, December 1987.
- NRC88** Standards for Protection Against Radiation, U.S. Code of Federal Regulations, Title 10, Part 20, January 1988, as amended.
- PAR89** Telephone Communication with Mr. Marc Parrotta, Environmental Protection Agency, Office of Drinking Water, Washington, DC, September 27, 1989.
- PAR88** Telephone Communication with Mr. Marc Parrotta, Environmental Protection Agency, Office of Drinking Water, Washington, DC, September 14, 1988.
- REI85** Reid, G. W. et al., Treatment, Waste Management and Cost of Radioactivity Removal from Drinking Water, Health Physics Journal, Vol. 48, May 1985.
- SOR88** Sorg, T.J., Methods for Removing Uranium from Drinking Water, AWWA Journal, July 1988.
- WIS75** Guidelines for the Application of Wastewater Sludge to Agricultural Land in Wisconsin, Department of Natural Resources, Technical Bulletin No.88, Madison, Wisconsin 1975.
- WIS85** Municipal Sludge Management, Chapter NR 204, Bureau of Natural Resources, Register, March 1985, No. 351, Madison, Wisconsin, 1985.
- WIS88** Interim Guidelines for the Disposal of Liquid and Solid Waste Containing Radium from Wisconsin Water Treatment Plants, Prepared by the State of Wisconsin, Bureau of Solid Waste Management, Drafts of August and October 1988.

B.7 METAL MINING AND PROCESSING WASTE

7.1 INTRODUCTION

The mining and processing of ores for the production of metals generates large quantities of residual bulk solids and wastes. Because the minerals of value comprise only a very small fraction of the ore, most of this bulk material has no direct use. It has been estimated that the mining and processing of ores and minerals, other than uranium and phosphate, has resulted in 41 billion metric tons (MT) of mine waste and tailings from 1910 to 1981 (EPA85). This industry typically generates about 1 billion MT of waste per year, including waste rock and overburden, ore tailings, and smelter slag. The quantity of waste materials and their physical and radiological characteristics differ widely among the various metal mining and processing industries. In addition, depending on the processing methods employed, some of the processing residues can contain elevated concentrations of naturally-occurring radionuclides. Mineral residues stockpiled at any one site are not always necessarily waste. Some tailings are in fact additional resources which may be subjected to further processing to extract additional minerals. Smelter slag may be processed for the extraction of additional minerals or it may be used as an additive in a variety of applications.

Because of the paucity of data, the waste generated by this sector is poorly understood. The literature contains only a few studies on the metal mining industry and in most cases, a few specific sites were evaluated for each type of metals. In addition, the characterization of some of the metal mining industries was based on very limited field sampling and analysis programs.

In July, 1990, the EPA published a document titled "Report to Congress Special Wastes from Mineral Processing" (EPA90). This report provides information on waste volumes, radionuclide concentrations, and commercial uses of processing wastes (slag and leachate) from the smelting and refining of mineral ores to produce primary metals. Information is included on wastes from the production of aluminum, copper, ferrous metals (iron and steel), lead, titanium, and zinc. Only very limited data are provided on NORM concentrations in these wastes. The EPA used screening criteria of 5 pCi/g of Ra-226 and

10 pCi/g of U-238 or Th-232 to define radionuclide concentrations in waste or leachate samples that could endanger human health.

Radionuclide concentrations in waste samples from the production of aluminum and titanium are reported in EPA90 that exceed these criteria. In slag samples from processing copper ores, Ra-226 concentrations are reported to be less than 5 pCi/g. No data on radionuclide concentrations in waste samples from the production of ferrous metals, lead, or zinc are given in the report.

It is generally believed by geologists that the presence of naturally-occurring radioactivity is more dependent upon the geological formation or region than on a particular type of mineral ore. It will also be apparent from reading the remainder of this section that ores often contain many different minerals. Accordingly, it cannot be assumed that the radionuclide content of one type of ore and its associated waste will be representative of a metal industry.

There have been reports that some of the more uncommon metals have highly radioactive waste products. Also, some of the processes associated with metal extraction appear to concentrate radionuclides and enhance their environmental mobility. Some published information and data to support these arguments have been presented, but in most cases it is suggested that further studies be conducted prior to reaching any conclusions.

The processes associated with aluminum, copper, zinc, tin, titanium, zirconium, hafnium, ferrous metals (iron and steel), and lead are discussed in this section. Elemental phosphorous is described in Section B.2. The minerals and metals described in this section were not really selected, but rather included because the availability of information and data. Some of the other metals, such as gold and silver, may be found in copper ore, and may also exist in other types of geological settings and at different abundances. No information was available for ores processed primarily for gold, silver, or molybdenum. However, it is generally recognized that pitchblende ore with high uranium content has been found in old precious metal mines or mine waste. Therefore, it is not reasonable to dismiss these or any other metal industries as being free of NORM waste based only from the available information.

In the sections that follow, an overview is provided of metal mining followed by a discussion of a number of metal mining and processing industries. A description of the properties of such mining waste and its potential to generate enhanced sources of naturally-occurring radioactive materials is also presented. Estimates of the actual and projected waste generation rates are also given for this NORM sector. This information is used to assess potential exposures to members of the general public and critical population groups. A radiological risk assessment is performed (see Chapter D) assuming that the exposed population is residing near a generic site.

7.2 OVERVIEW OF THE METAL MINING INDUSTRY

Mineral ores are mined by both surface and underground mining methods. In many respects, the mining methods characterizing the uranium mining industry also apply to metal mining (see Section B.1 for details). For the sake of simplicity and to avoid some redundancy, the radiological characteristics of each metal mining segment are included in this Subsection. Section 7.4 provides a summary and highlights the radiological data presented in the following subsections.

7.2.1 Metal Mining and Waste Production

The bulk of residual material from metal mining and processing is the soil or rock that mining operations generate during the process of gaining access to an ore or mineral body. This material includes the overburden from surface mines, underground mine development rock, and other waste rock, including rock and ore. In 1986, the total solid material handled at all surface and underground mines in the U.S. was 2,385 million metric tons (MT). Of this, metal mines handled 989 million MT (DOI87). The mine piles cover areas ranging from 2 to 240 hectares, with an average area of 51 hectares. Some of this bulk material may be considered waste, while other portions of it have economic value as low grade ore or for use in other applications.

After the ore is mined, it undergoes beneficiation where the crushed ores are concentrated to free the valuable mineral and metal particles (termed values) from the matrix of less valuable rock (called gangue). Beneficiation processes also include physical and chemical separation techniques such as gravity concentration, magnetic separation, electrostatic separation, flotation, ion exchange, solvent extraction, electrowinning, precipitation, and amalgamation. The choice of beneficiation process depends upon the properties of the metal or mineral ore and the gangue, the properties of other minerals or metals in the same ore, and the relative costs of alternative methods. Almost all processes generate tailings, which may be considered waste material or may have economic value for subsequent mineral extraction.

Tailings are the materials remaining after physical or chemical beneficiation removes the valuable constituents from the ore. Tailings generally leave the mill as a slurry consisting of 50 to 70 percent (by weight) liquid mill effluent and 30 to 50 percent solids (clay, silt, and sand-sized particles). Significant quantities of slag and sand may also be generated from some high temperature extraction processes.

More than half of the mill tailings are disposed in tailings ponds, which also serve as the primary method to treat wastewater in the metal mining industry. Settling ponds are also used at several mineral mining processing sites for the management of liquid waste. Pond size and design vary by industry segment and mine location. Some copper tailings ponds in the southwest cover 240 to 400 hectares (one exceeds 2,000 hectares), while some small lead/zinc tailings ponds cover less than 1 hectare. Based on a Bureau of Mines survey of 145 tailings ponds in the copper, lead, zinc, gold, and silver industries, the average size of these ponds is approximately 200 hectares. Many facilities use several ponds in series to improve the treatment process. Multiple-pond systems offer other advantages as well, as the tailings themselves are often used to construct dams and dikes.

Technological advances have made it economically feasible to beneficiate ores taken from lower-grade ore deposits (i.e., those with much higher waste-to-ore ratios). For example, froth flotation beneficiation processes have had a significant impact on mine production and upon waste generation. Not only have these advances increased mining production, but the volume of waste generated also has risen dramatically. The tailings from froth flotation operations are generally alkaline because the process is more efficient at higher pH levels.

The metals in the alkaline tailings solids are believed to be immobile, unless chemical conditions change over time.

Dump leaching, heap leaching and in situ leaching are other processes used to extract metals from low-grade ore. In dump leaching, the material to be leached is placed directly on the ground. Acid is applied, generally by spraying, although many sulfide ores will generate acid during wetting. As the liquid percolates through the ore, it leaches out metals. The leachate, "pregnant" with the valuable metals, is collected at the base of the pile and subjected to further processing to recover the metal. Dump leach piles often cover hundreds of hectares, rise to 60 meters or more, and contain tens of millions of metric tons of low-grade ore, which becomes waste after leaching.

7.2.2 Bauxite and Aluminum

Bauxite is an ore containing hydrated aluminum oxide minerals, such as gibbsite, boehmite, or diaspora and is formed by the weathering processes on aluminum bearing rocks. Impurities in bauxite consist of Fe_2O_3 , SiO_2 , and TiO_2 (CRC81). Most bauxite is imported from countries in Africa and South America and from Jamaica. In 1986, only 522 thousand MT were mined in the United States while the amount used was 6,978 thousand MT (DOI87). Two surface mines in Arkansas have been responsible for all recent bauxite mining in the United States.

The only ore beneficiation operations performed at these mines include crushing and grinding. Water used for dust suppression, mine dewatering, and surface runoff results in the generation of a small volume of wastewater. This water is neutralized by lime and discharged into nearby streams (EPA78a).

Bauxite refineries produce alumina (Al_2O_3) which is used as a feedstock for the aluminum reduction industry. By late 1989, five facilities in the United States were active for domestic alumina production (EPA90). The locations and ore sources for these facilities are shown in Table B.7-1. The total annual production capacity for the domestic bauxite refining industry, as reported by these facilities, is approximately 4.9 million MT. The total reported 1988 production of alumina was 4.086 million MT.

Table B.7-1. Bauxite refineries.
(Source: EPA90)

Owner	Location	Ore Source (1982)
ALCOA	Bauxite, AR	U.S. (Bauxite, AR)
ALCOA	Point Comfort, TX	Confidential
Kaiser	Gramercy, LA	Jamaica
ORMET	Burnside, LA	Sierra Leone, Brazil, Guyana
Reynolds	Gregory, TX	Australia, Jamaica, Brazil, Guinea

Bauxite ore is processed at an alumina plant using the Bayer or a modified Bayer process. Dried bauxite is mixed with a caustic liquor in slurry tanks, transferred to heated digesters where additional caustic is added to dissolve the alumina from the bauxite. The liquor is then pumped through settling tanks to remove the bauxite residue. This spent bauxite residue, called "red mud", is placed in a tailings impoundment near the plant. Red mud in some plants is processed to remove sodium aluminum silicate in the form of pure chemical grade alumina hydrates. The waste product is called "brown mud". Hydrated aluminum oxide is precipitated from the liquor and heated in rotary kilns to drive off water to produce aluminum oxide. The alumina can be further processed, transferred, or sold to another facility.

The refinery muds contain significant amounts of iron, aluminum, calcium, and sodium. They may also contain trace amounts of elements such as barium, boron, cadmium, chromium, cobalt, gallium, lead, scandium, and vanadium, as well as radionuclides. The types and concentrations of minerals present in the muds depend on the composition of the ore and the operating conditions in the digesters. The material is caustic and no use has been made of impounded muds. However, muds might be used for land reclamation, for the construction of site dams or embankments, or as a feed material for other extraction processes because of the iron content.

A study conducted by the EPA (EPA82a, EPA78a) indicates that the refinery process generates about one ton of solid waste during the production of one ton of aluminum. This includes a small amount of waste rock, the red and brown muds, and a small amount of scrap and solid wastes coming from the smelter. The red and brown muds are precipitated from a caustic suspension of sodium aluminate in a slurry and routed to large on-site surface impoundments. In these impoundments, the muds settle to the bottom and the water is removed, treated, and either discharged or reused. The muds dry to a solid of very fine particle size (sometimes less than 1 μm). In aggregate, the industry-wide generation of red and brown muds by the five domestic bauxite refineries, shown in Table B.7-1, was approximately 2.8 million MT in 1988 (EPA90).

The impoundments that receive the muds typically have surface areas between 44.6 and 105.3 hectares, although one impoundment is only 10.1 hectares and another is almost

1,300 hectares. The depth of the impoundments range from 1 to 16 meters, with an average impoundment depth of 7 meters. As of 1988, the quantity of muds accumulated onsite at the five facilities ranged from 500,000 to 22 million MT per facility, with an average of 9.7 million MT per facility.

In order to characterize the radiological properties of such wastes, the EPA conducted a radiological evaluation of a mine and associated aluminum processing plant (EPA82a). The selected site was a surface mine with several open pits ranging in size from 0.3 to 3 hectares. The overburden and waste and rock were placed into previously mined pits. The bauxite ore was found to be elevated in both U-238 and Th-232, with concentrations of 6.8 and 5.5 pCi/g. The Ra-226 concentration was noted to be higher than that of U-238, at 7.4 pCi/g. Po-210 and Pb-210 concentrations were higher still, at 10 and 9.1 pCi/g, respectively.

The concentrations of these radionuclides in red mud were noted to be about the same as that of bauxite. In brown mud, the concentrations were notably lower, except for thorium which was higher than either bauxite or red mud. Table B.7-2 presents radionuclide concentrations measured in bauxite ore and alumina samples. Data on radionuclide concentrations in refinery muds are also available from industry responses to a RCRA §3007 request in 1989 and from a 1985 sampling and analysis effort by EPA's Office of Solid Waste (OSW) (EPA90). Data on three mud samples gave a median Ra-226 concentration of 14.1 pCi/l and a median U-238 concentration of 8.75 pCi/l.

Radon-222 flux measurements were made using charcoal canister on ore bodies, overburden materials, spoil areas, and in open pits. The measurement results indicated varying radon surface flux rates, ranging from a low 2.6 to as high as 62 pCi/m²-s. The local background radon flux rate was reported to be 0.38 pCi/m²-s. Table B.7-3 presents individual and average radon flux rates for different locations at the mining site.

7.2.3 Copper

The copper industry is primarily located in the arid western United States. In 1986, there were a total of 18 operating mines which moved a total of 468 million MT of ore (DOI87). The amount of marketable copper is small compared with the material handled.

**Table B.7-2. Radionuclide concentrations in alumina plant process samples.
(EPA82a)**

Sample	Radioactivity Concentrations (pCi/g)^a							
	U-238	U-234	Th-230	Ra-226	Pb-210	Po-210	Th-232	Th-228
Bauxite Ore	6.8±0.7	6.9±0.7	6.4±1.1	7.4±2.2	9.1±1.1	10.0±1	5.5±1.0	5.5±1.0
Blended Bauxite	4.0±0.5	4.0±0.5	3.5±0.3	4.4±1.3	5.3±0.4	4.2±0.5	5.2±1.2	5.6±1.2
Alumina Kiln Feed	0.05±0.03	0.07±0.03	<0.05	0.08±0.05	0.20±0.15	0.00±0.20	<0.05	<0.05
Alumina Product	0.28±0.10	0.28±0.10	<1	0.23±0.07	<1.4	<0.6	<0.2	<0.2
RC-64 Alumina	0.31±0.09	0.35±0.10	<0.6	0.19±0.06	<1.3	<0.6	<0.2	<0.2
Red Mud Filter Cake	7.5±1.2	7.5±1.2	5.1±1.3	6.5±2.0	7.6±0.4	7.7±1.7	6.0±1.5	6.3±1.5
Prepared Sinter Mud	4.8±0.5	4.7±0.5	4.2±1.1	3.9±1.2	6.8±0.4	4.6±0.5	5.0±1.3	5.5±1.4
Sinter	6.4±0.8	6.6±0.9	6.5±1.6	3.9±1.2	3.6±0.4	3.2±1.2	9.2±2.1	8.6±2.0
Brown Mud^b	5.5±0.4	5.6±0.5	8.0±2.7	5.6±1.2	5.7±0.8	5.4±0.7	12.5±4	12.5±4

^a Picocuries (10⁻¹² curies) per gram plus or minus twice the standard deviation based on counting statistics.

^b The results are derived from duplicate samples.

Table B.7-3. Bauxite open-pit radon surface flux rates.^a

Location	Radon Surface Flux Rate^b
Top of ore body	35
Top of ore body	62
Top of ore body	39
Average	45
Top of overburden - topsoil removed	5.9
Overburden sidewall, 5 ft. below top	13
Overburden sluffage berm, midway between surface and top of ore	2.6
Average	7.2
Spoils area	4.9
Spoils area	12
Average	8.5
Pit background, undisturbed soil	27
Pit background, undisturbed soil	9.6
Pit background, undisturbed soil	16
Pit background, undisturbed soil	35
Average	22

a Data extracted from EPA82a.

b Units are in picocuries per square meter per second. There are 10^{-12} curies in one picocurie.

Over 300 MT of ore must be handled for each metric ton of copper metal produced. Thus the waste quantities are very large. Because of the large quantities of waste, the processing facilities are usually located near the copper mines.

The vast quantities of ore, overburden, and rock are segregated, at the mine site where the rock is hauled by truck to the rock dump. The ore is then crushed and mixed with other low-grade ore and is chemically leached to remove the copper. The higher grade ore is further milled and the end product is concentrated by physical separation, such as a flotation process. The tailings are pumped to the tailings pile and the copper concentrate is transported to a nearby smelter.

The locations of ten primary copper processing facilities that, as of September 1989, were active in the smelting and refining of copper concentrate are shown in Table B.7-4.

During the early 1980s, production of copper in the U.S. declined as a result of a drop in copper prices. However, primary production of copper in the U.S. increased throughout the late 1980s. Between 1986 and 1989, production from domestic and imported raw materials increased by 38 percent. Imports of refined copper for consumption decreased by 40 percent (from 502,000 MT to 300,000 MT), while exports increased 833 percent (from 12,000 MT to 100,000 MT) (EPA90). Most smelting and refining facilities have recently undergone modernization. The total annual primary copper smelting production capacity currently stands at about 1.27 million MT per year of anode copper; the primary copper refining capacity is about 1.33 million MT per year of refined copper.

The demand for copper is closely tied to the overall economy, and demand remained relatively flat through the late 1980s. Total apparent consumption of copper in the U.S. rose slightly from 2.136 million MT in 1986 to 2.250 million MT in 1989. Future demand depends upon the health of the economy. Almost 40 percent of the 1988 U.S. consumption of copper went to the building and construction industries, while about 23 percent was used by the electrical and electronic industries. Industrial machinery and equipment, the power generation industry, and the transportation industry together consumed 38 percent of the copper produced in the U.S. in 1988 (EPA90).

Table B.7-4. Primary copper processing facilities.
(Source: EPA90)

<u>Owner</u>	<u>Location</u>	<u>Type of Operation</u>		
		<u>Smelter and Converter</u>	<u>Anode Furnace</u>	<u>Electrolytic Refinery</u>
ASARCO	Amarillo, TX	No	Yes	Yes
ASARCO	El Paso, TX	Yes	Yes	No
ASARCO	Hayden, AZ	Yes	Yes	No
Kennecott	Garfield, UT	Yes	Yes	Yes
Copper Range	White Pine, MI	Yes	Yes	Yes
Cyprus	Claypool, AZ	Yes	Yes	Yes
Magma	San Manuel, AZ	Yes	Yes	Yes
Phelps Dodge	El Paso, TX	No	Yes	Yes
Phelps Dodge	Hurley, NM	Yes	Yes	No
Phelps Dodge	Playas, NM	Yes	Yes	No

In 1986, there were 172 million MT of crude ore handled from copper mines in the United States. In addition, 295 million MT of waste were processed for disposal. Only 5 percent of this material came from underground mines (DOI87). Note that this is significantly less than the 723 million MT of waste handled at copper mines in 1980 (EPA85). For copper mines (1980 data), approximately 33 percent of the waste is tailings, 28 percent are dump and heap leach wastes, and 39 percent is comprised of waste rock and overburden. This distribution is believed to still represent current practices.

Tailings piles vary in size, but may be as large as 400 hectares for copper mines in the southwest. The waste rock and leach piles may also reach 400 hectares each. A study of 12 tailings piles (EPA85) revealed that no tailings pile liners were used and only two sites were reported to monitor ground water. Such data is misleading in that New Mexico, Arizona, Colorado, and California require ground water monitoring since these states already have a large number of existing mill tailings piles. Some of the copper mine wastes have been put to use, but on a limited scale. Mixtures of crushed waste rock, including waste rock from the copper mines, have been used to construct embankments, fills, or pavement bases for highways. Some bench scale studies have shown that copper tailings can be used in bricks if pyrites are first removed (EPA85).

The three steps in copper smelting consist of roasting, smelting, and converting. The copper ore concentrates are roasted or heated in an oxidizing atmosphere which partially drives off some of the sulfur as sulfur dioxide. Where roasters are not employed, the ore is dried by heating in a rotary dryer if the concentrate has a high moisture content.

The smelting stage consists of using a smelting furnace to melt and react copper concentrates and/or calcine in the presence of silica and limestone flux to form two immiscible layers. One of the layers is waste consisting of iron and silica compounds, which is discarded on the slag pile. The other layer called "matte copper" consists of copper and iron sulfide and other metals.

The matte copper is placed in a converter where silica flux is added, and the resultant mixture is air blown to produce a copper rich slag, which is returned to the crusher. The remaining molten mass is then air blown to convert the copper sulfide to blister copper which is transferred to an anode furnace for casting.

The typical copper concentrations were noted to range from 0.5 to 1.0 percent in copper ores used by a smelter evaluated by the EPA (EPA78a, EPA78b). All ores with an abundance of 0.3 percent or less are rejected as waste rock. Since the concentrate feed rate to the smelter is approximately 3 times that of the copper production rate, in a reverberatory furnace (smelter) slag is produced at a rate which is about 75 percent that of the incoming copper concentrate. The EPA's report to Congress on special wastes from mineral processing (EPA90) indicates that 2.5 million MT of smelter slag and 1.5 million MT of slag tailings were generated by copper smelting and refining facilities in the U.S. in 1988. The slag waste volume from copper smelting and refining is very small compared to the overburden and tailings waste volumes from mining and beneficiation operations.

At the eight active copper smelters (Table B.7-4) smelter slag is initially deposited on waste piles. These slag piles range in surface area from about 1 to 30 hectares, and in height from 3 to 45 meters. Slag accumulations in individual piles ranged from 0.5 to 21 million MT as of 1988.

Three smelters (San Manuel, White Pine, and Garfield) subsequently process all their smelter slag either in a conventional ore concentrator or in a stand-alone slag concentrator. The slag tailings from these operations are co-managed at on-site tailings piles with the tailings from ore beneficiation. Slag tailings ponds range from 142 to 2,270 hectares with an average size of about 600 hectares. Depths range from about 16 to 61 meters with an average depth of 46 meters. As of 1988, quantities of slag tailings in these ponds ranged from 240,000 MT to 3.4 million MT, with an average of 1.8 million MT.

Copper slag may be used as a source of secondary metals and in various applications in road and building construction. Research has been conducted on removing secondary metals such as iron, nickel, and cobalt from copper slag, but commercial facilities for metals recovery are not currently in operation. Copper slag has been used as an aggregate in asphalt and seal coats in highway construction in Arizona and Utah, which are among the top generators of copper slag. It can be used as a source of aggregate in portland cement concrete. It has also been used for road cinderling, as granules for roof shingles, as pipe bedding, and in road beds when mixed with a sufficient quantity of road rock. Copper slag was used in construction of a large portion of the Southern Pacific railroad roadbed from New Orleans to San Francisco.

Several EPA studies have reported uranium and thorium concentrations in various copper mining and processing materials. Unfortunately, the primary goals of these studies were not to perform a radiological characterization, and thus very little relevant data were obtained. The locations of the study sites were not identified, but it is known that one of the sites was in the Southwest (Arizona or New Mexico). Table B.7-5 summarizes the results of these studies. The EPA's report to Congress on special wastes from mineral processing (EPA90) reported Ra-226 concentrations in samples of copper slag to be less than 5 pCi/g.

From this information, it might be concluded that radionuclide concentrations, copper mining, and processing wastes are at about the natural crustal abundance. However, a review of available information for the State of Arizona, where much of the copper is produced, might lead to a different conclusion.

Uranium has been found in many primary metals deposits in Arizona where it is associated with copper and molybdenum in large porphyry copper ore bodies and in vein deposits with copper, lead, and zinc sulfides. Uranium is also known to occur in significant quantities in oxide and sulfide ores. Table B.7-6 presents a summary of uranium bearing metalliferous deposits in selected Arizona mining sites. The following discussion highlights some of the important findings noted at these sites.

The presence of uranium has been documented at the Esperanza mine, located in the southeastern Sierritas about 25 miles SSW of Tucson and 10 miles SW of the community of Sahuarita. Assay results of stockpiled ore indicate that U_3O_8 is present at 0.11 to 0.18 percent (PEI70).

The Twin Buttes mine lies roughly four miles northeast of Esperanza and about 23 miles south of Tucson. At Esperanza, uranium, as uraninite and secondary uranium minerals, has been found with molybdenite and copper minerals. Whether or not these are from oxide ores originating from early open pit operations (as at Twin Buttes) or from sulfide ores, perhaps from earlier underground mining, is uncertain. Twin Buttes and Esperanza are only two of a number of fairly large open-pit porphyry copper-molybdenum producers found on the east side of the Sierrita Mountains, southwest of Tucson. Other mines, Pima-Mission, and San Xavier are in fact closer to Tucson, about 16 miles away. The absence of uranium

Table B.7-5. Radionuclide concentrations in copper materials.

Material	Radionuclide Concentrations (pCi/g)^a			
	EPA-79	EPA-83^b	EPA82a	
			Underground	Open Pit
Ore:	---	---	0.79(0.62)	2.2(3.1)
Surface mine waste:	---	0.8-1.78	---	---
Ore concentrates:	0.7(0.8)	---	0.65(0.07)	1.4(1.1)
Tailings:	---	0.02-1.48	0.82(0.24)	1.6(3.0)
Furnace slag:	3(5)	---	---	---
Leach material:	---	1.19-2.99	---	---

a The results are for U-238, those in parenthesis are for Th-232.

b For plants located in Arizona or New Mexico and at other unspecified locations.

Table B.7-8. Selected uranium bearing metalliferous deposits in Arizona.

Name	Location	Mining District County	Principal Commodity(ies)	Type of Mine	Th Association	Assays Reported	Ref.
Twin Buttes	E Sierrita Mountains, SW of Tucson	Pima Dist. Pima Co.	Copper	Open pit porphyry copper	Uranium in oxide ore	Unknown; produced yellow cake 1980-1985	(Peirce 70)
Esperanza	SE Sierrita Mountains, SW of Tucson	Pima Dist. Pima Co.	Copper, molybdenum	Open pit porphyry copper	Uranium with copper and molybdenum mineralization	0.111-0.182% eU ₃ O ₈ -old ore	(Beard 89)
Bisbee	Bisbee, AZ	Warren Dist. Cochise Co.	Copper	Open pit	Uraninite in zones in sulfide ore bodies, hematite, quartz	Not given	(Beard 89)
Morenci	Morenci, AZ	Copper Mountain Greenlee Co.	Copper	Open pit porphyry	Scattered uranium mineralization associated with copper	Not given	(Beard 89)
Copper Sqaw	Quijotoa Papago Indian Reservation	Quijotoa Dist. Pima Co.	Copper	Old property vein	Uranium associated with oxidized copper and iron	0.76-1.4% eU ₃ O ₈	
Black Dike	NW Sierrita Mountains, W of Tucson	Papago Dist. Pima Co.	Prospect	Shaft with dumps	Pitchblend with MnOx, Cu Sulfides and fluorite	0.011-0.16 to U (=U ₃ O ₈)	(Beard 89) (McDonnell 89)
King Mine	Northern Santa Rita Mountains, S of Tucson at Helvita	Helvita Dist. Pima Co.	Silver, copper	Vein; underground old workings area drilled out for porphyry copper	Pitchblend with Fe and Cu sulfides	0.14-0.934 eU ₃ O ₈	(Beard 89) (Peirce 70)
Gismo group	Las Guevas Mountains SW of Tucson, SW of Twin Buttes, Esperanza	Las Guevas Dist. Pima Co.	Gold-silver	(Old mining area) veins	Uranium minerals associated with copper and iron	0.12-0.30% U ₃ O ₈	(Beard 89)
Miscellaneous near Patagonia	Southern Santa Rita Mountains close, N of Nogales	Wrightston Dist. Santa Cruz Co.	Silver-base metals (lead)	U-secondaries associated with Galena (PBS)	Uraninite and old lead-silver and silver base metal workings-veins	0.02-0.07% eU ₃ O ₈	(Peirce 70)
Hillside	Near Bagdad (3 miles north)	Eureka Dist. Yavapai Co.	Gold, silver, zinc, lead	Underground vein	Uranium secondary minerals found on drift walls. Pitchblend also reported with gold, silver, base metals, and fluorite	(tr)>0.11% eU ₃ O ₈ with an assay of 2.3%	(USGS 63) (Peirce 70)
Miscellaneous Cerbat Mountain mines	Cerbat Mountains N of Kingman	Cerbat Mohave	Base and precious metals	Old mines, veins	Uranium minerals with quartz and base metal sulfides	0.01-0.5% U ₃ O ₈	(Peirce 70)

at these mines does not preclude its presence as the geology and mineralogy is fairly similar (BEA89).

Uranium is found in various base metal deposits in a band extending at least 10 miles northwest from Twin Buttes and Esperanza, cutting across the Sierrita Mountains. This band tentatively ends at the now non-producing Black Dike Mine located on the northwest side of the Sierrita Mountains, some 27 miles SW of Tucson. At this site, uranium in abundance as high as 0.16 percent has been found in a contact zone of U_3O_8 exposed by a shaft associated with copper minerals and fluorite mining (PEI70). On the surface, dumps with copper oxides, sulfides, and purple fluorite have been observed with anomalous radioactivity levels (MCD89).

At the much smaller nearby Black Dike mine, uranium has been found in varying amounts with sulfide base metals, mainly in vein like deposits (PEI70).

Elevated levels of uranium have also been observed in the Tucson region, outside of the Sierritas. The King mine, an old silver and copper mine, is one of several in the area where pitchblende occurs (with sulfides) with assay results ranging from 0.14 to 0.93 percent U_3O_8 (PEI70). The mine is located on a contact zone exposed by underground mine workings. It appears that this mine is one of several which have been developed under recent exploration efforts (BEA89).

Other Arizona uriferous-metallic occurrences are known to exist in or near other large copper mines in Arizona. Uranium is present in sulfide ore bodies at Bisbee, where it is associated with quartz and hematite (PEI70, USG63) and is found in trace amounts scattered along with copper mineralization at Morenci (PEI70). No assay results were given in any of the reviewed literature. The Morenci mine is a large open-pit porphyry copper mine located in the eastern part of the state, northeast of Safford. Bisbee is also an open-pit copper mine, located near the Mexican border, between Douglas, Sierra Vista, and Tombstone.

Uranium is found in trace amounts, at an average of 0.0055 percent U_3O_8 , in porphyry copper deposits in the Miami district, east of Phoenix (STI62). Uranium has also been found in copper sulfide in schist veins near Globe (MCD89). It is not known if such deposits exist

at the San Manuel, Ray, and Christmas mines, which are widely dispersed between the north side of the Santa Catalina Mountains north of Tucson and the Dripping Springs Mountain.

Uranium occurs in the Bagdad District, some 35 miles west of Prescott, with U_3O_8 concentrations being as high as 2.3 percent in the Hillside mine (USG55). The Hillside mine is an old mine (gold - silver - zinc - lead) located on a fissure vein. The abundance of uranium at this location is probably much less, perhaps closer to 0.1 percent U_3O_8 (PEI70).

The data on uranium occurrences in metalliferous deposits in Arizona, summarized in Table B.7-6, probably reflects a biased sampling program. Still (STI62) has reported results for 441 ore samples taken in the Miami district of Arizona for which he cited U_3O_8 concentrations as high as 0.018 percent, with a mean of 0.016 percent. While it is possible to find copper mining wastes with uranium concentrations that are typical of pitchblende, it is probable that large site averages are much less, being probably closer to 0.01 percent. This corresponds to U-238 concentrations in the waste of about 34 pCi/g.

Based on this review, it is difficult to characterize the radiological properties of overburden and tailings associated with the mining and processing of copper ores. The data presented above do not indicate that radionuclides are concentrated in any of the waste streams. However, elevated exposures may be associated with the use of materials from waste rock piles, leach piles, furnace slag piles, and tailings piles. A more detailed survey of wastes and tailings, especially from the copper mines and mills of Arizona and New Mexico is warranted to better characterize these potential NORM wastes.

7.2.4 Zinc

In 1987, approximately 50 percent of the production of zinc ore was from Tennessee, with New York, Missouri, and 8 other states sharing the balance (DOI87). The 1987 ore production was 216,981 MT (DOI89). In 1989, U.S. production of mined zinc rose to 300,000 MT (EPA 90). By 1991, U.S. mine production of zinc could double that of 1989, due primarily to the large Red Dog, Alaska mine, which opened in November 1989 (BOM90). A major factor leading to the increased production of mined zinc has been the strong demand from the

automobile industry for galvanized sheet metal. Galvanizing accounted for 45 percent of zinc consumption in 1989.

Zinc processing facilities in the U.S. include one at Monaca, Pennsylvania which uses pyrometallurgical (smelting) techniques and three additional facilities that use electrolytic production techniques. In 1988, the Monaca facility produced 99,800 MT of zinc and 157,000 MT of zinc slag.

At the Monaca facility, the furnace slag is crushed and separated into four material streams: zinc fines, reclaimed coke, processed slag, and ferrosilicon. The fines and coke are recycled to beneficiation and processing operations at the facility. The processed slag and ferrosilicon are placed on slag piles. The processed slag pile covers an area of about 1.2 hectares and is roughly 7 m in height. The ferrosilicon pile has a basal area of 8,000 square meters and is also about 7 m high. In addition, slag has been placed in a layer at the bottom of the facility's flyash landfill that is approximately 0.3 m deep and covers an area of about 8 hectares. As of 1988, quantities of waste accumulated in the ferrosilicon pile, processed slag pile, and the landfill were about 48,000, 63,500, and 45,400 MT, respectively.

Slag at the Monaca facility has been used as gravel on parking lots and other areas of the plant site. It has also been used as railroad ballast, as an aggregate in asphalt, and as an anti-skid material.

The EPA has conducted a characterization study of a large underground zinc mine and mill (EPA82b). The study revealed that the presence of U-238 and Th-232 and their decay products were found in ores, concentrates, and tailings at less than 20 percent of the average crustal abundances. The EPA's report to Congress on special wastes from mineral processing does not include any information on U-238, Th-232, or Ra-226 concentrations in zinc smelter slag. Since concentrations of these nuclides were to be included in measurements made to characterize mineral processing wastes, it may be concluded that any measured concentrations were below the EPA's screening criteria (10 pCi/g for U-238 and Th-232, and 5 pCi/g for Ra-226). It would, therefore, appear that the overburden, subore, tailings, and smelter slag associated with the zinc mining and processing industry do not represent a

significant source of NORM wastes. Considering their use as construction materials further radiological characterizations of zinc mining and processing wastes may be warranted.

7.2.5 Tin

Competitive pressures and a world wide excess in tin inventory have caused many mine closures in recent years. Only one U.S. mine, located in Alaska, produced ore concentrates in 1986, but no specific production data were available. However, this mine is reported to produce only a small fraction of the total U.S. consumption (DOI87). The other domestic tin producer is Tex Tin Corp., located in Texas City, Texas. This facility processed domestic and imported ores, primarily from Peru. In 1987, the U.S. imported 2,953 MT of concentrates. Total smelter production has been reported to be 3,905 MT (DOI87).

Amang is a general term for the by-products obtained when tin tailings are processed into concentrated ores. It includes minerals, such as monazite, zircon, ilmenite, rutile, and garnet. Hu reported analytical results for amang coming from Malaysia, including monazite, xenotime, zircon, and thorium cake (HU85). While it is not known how the levels of radioactivity in amang compares with titanium concentrates, Ra-226 and Th-232 activities in amang were reported to range from 430-480 pCi/g and 1,160-8,830 pCi/g, respectively. Accordingly, tailings from these ores appear to have a significant potential to cause elevated radiation exposures, if used indiscriminately.

Gamma survey measurements made at the Tex Tin smelter revealed uncorrected radiation levels in slag storage areas ranging from 10 μ R/h to 500 μ R/h, with average levels of less than 60 μ R/h. Four samples taken from such areas revealed U-238 concentrations up to 43 pCi/g and Th-232 concentrations up to 19 pCi/g (CRC81). The State of Texas has conducted some measurements at the Texas City Site (GRA89). Two slag pile samples, taken in August of 1988, showed Ra-226 concentrations of 7.3 and 55 pCi/g. Uranium concentrations were noted to be 17 and 34 pCi/g, while those for Ac-228 (Th-232 series) were found to be lower at 2.9 and 7 pCi/g. No information was available regarding past uses or possible applications of the slag from this tin smelter. No information on tin slag is given in the EPA's report to Congress on mineral processing wastes.

7.2.6 Titanium

U.S. titanium ore and concentrate supplies are obtained primarily from Australia, South Africa, and Canada. The concentrates are produced from rutile (TiO_2), leucoxene (TiO_2), and ilmenite (FeTiO_3), as well as from titanium slag. Titanium is also found with iron ore (titaniferous) which is imported from Canada. Titanium ore and concentrates are processed by chlorination in a fluidized-bed reactor in the presence of coke to produce titanium tetrachloride which is used as a feedstock to two major processes, production of titanium dioxide and titanium sponge. Titanium dioxide is used primarily as a pigment in the paper and paint industries; titanium sponge is used primarily in aircraft engines and airframes. Nine facilities, located across the U.S., that were active in 1989 in the production of titanium tetrachloride are shown in Table B.7-7.

The production and consumption of titanium metal in the U.S. has generally been increasing because of its demand in the aerospace industry, mainly aircraft engines and airframes manufacturing. While aerospace applications make up 78 percent of the use of this metal, other applications are common where high-strength toughness, heat resistance, and high structural integrity are needed. The use of titanium in automotive engines is being considered. The consumption of TiO_2 , e.g., as a paint pigment, is also increasing. In general, the demand is greater than existing world supplies (DOI87). Titanium metal production in the U.S. increased by 12 percent, from 21,000 MT to 24,000 MT, between 1985 and 1989 (EPA 90). Titanium oxide pigment production increased by 8 percent, from 927,000 MT to 1.007 million MT, during this same period.

The chlorination of titanium ores and concentrates to produce titanium tetrachloride produces chloride process waste solids. These solids are typically generated in a slurry with waste acids. The solids in the slurry are particles with a diameter less than 0.02 mm (smaller than sand). The aggregate industry-wide generation of chloride process waste solids was 414,000 MT in 1988. Waste solids are managed in surface impoundments and/or settling ponds. The waste solids piles are typically small, covering 0.5 to 5 hectares, and are about 1 to 10 meters in height. Recycling of waste solids to recover additional titanium and other metals such as columbium, tantalum, and zirconium is the primary management alternative to the current practice of neutralization and surface impoundment/landfill disposal. While laboratory tests have demonstrated the technical feasibility of recycling, no full-scale

**Table B.7-7. Domestic titanium tetrachloride producers.
(Source: EPA90)**

Owner	Location	Ore Type
E.I. duPont	Antioch, CA	Rutile
E.I. duPont	Edgemoore, DE	Ilmenite
E.I. duPont	New Johnsonville, TN	Ilmenite
E.I. duPont	Pass Christian, MS	Ilmenite
Kemira	Savannah, GA	Rutile
Kerr-McGee	Hamilton, MS	Synthetic Rutile
SCM	Ashtabula, OH	Rutile, S. African Slag
SCM	Baltimore, MD	Rutile, S. African Slag
TIMET	Henderson, NV	Rutile

applications are known to exist. No other uses of titanium waste solids are reported in the EPA's report to Congress on mineral processing wastes.

Much of the ore from which titanium is obtained originates in beach and fluviatile sands which also contain monazite. Impurities in monazite are present at high concentrations, and include uranium and thorium and their decay products. The concentration of these radionuclides is expected to vary from ore to ore (CRC81). Data gathered by the EPA indicate that in rutile and leucoxene ores, uranium and thorium were present at concentrations in the range of 5 to 20 pCi/g (CRC81). Radium in sludge from titanium-chlorination process streams was observed in concentrations as high as 77 pCi/g. Radionuclides in liquid waste streams were found to be similarly elevated.

Analyses of 12 samples of chloride process solid waste from one titanium tetrachloride producer showed a median Ra-226 concentration of 8.0 pCi/g with a range of 3.9 to 24.5 pCi/g (EPA 90). The median U-238 concentration for these 12 samples was 1.5 pCi/g with a range of 0.07 to 42.7 pCi/g. The median Th-232 concentration was 1.1 pCi/g with a range of 0.12 to 88.9 pCi/g.

7.2.7 Zirconium and Hafnium

The ores containing zirconium and hafnium are obtained as a by-product of mining and extracting titanium minerals, ilmenite and rutile. Zirconium and hafnium are found in mineral ore, zircon, in a ratio of 50 to 1. While hafnium is used to manufacture nuclear reactor fuel control rods, it has few other uses and the demand is relatively small. Zirconium, in the form of zircon, however, is widely used in foundry sands, refractory paints, and in other refractory materials. World resources are large when compared to current demands. The ores are primarily produced in Australia and the Republic of South Africa, which presently have over 40 percent of the worlds' zirconium mining capacity (DOI85). In 1984, there were 39 locations in the U.S. where zirconium materials were produced, primarily in the East. Zircon or zircon ores were processed in Cleveland, Ohio; Wilmington, Delaware; and Green Cove Springs, Florida. Zircon mineral concentrates are produced in Florida by E.I. duPont de Nemours & Co., and Associated Minerals Consolidated Inc.

Zirconium oxide is produced directly from zircon by either plasma fusion or electric arc techniques. For the electric arc technique, a clinker is eventually formed which disintegrates into a powder. The powder is air classified, and the zirconate crystals are treated with acids or other reagents to form oxides and salts. The plasma method heats the finely divided zircon concentrate above its dissociation temperatures, forming zirconia crystallites and glassy amorphous silica. The hot zirconium oxide is quenched rapidly and the glassy silica is leached out with sodium hydroxide solution, leaving the insoluble zirconia crystallites. There are several other more complex processes for producing this metal, however, such methods are costly and are not widely used.

Zircon and monazite are non-conductive and are separated from the titanium ores electrostatically. Monazite, which is slightly magnetic, can then be separated from zircon by electromagnets. Uranium and thorium are known to occur in high concentrations in monazite. The separation of U-238 and Th-232 from zircon (and monazite) has not always been accomplished successfully. An instance was cited (DOI85) in which mineral wastes on the property of a U.S. producer of zirconium metal contained more Ra-226 than could be legally allowed under state laws.

In recent years, zircon sands have been chlorinated directly in a fluidized bed containing carbon. This converts the zirconium content of zircon to tetrachloride. A potential source of significant amounts of NORM waste are believed to occur during the conversion process of baddeleyite (ZrO_2) concentrates originating from the Republic of South Africa (CRC87). The baddeleyite concentrate (97 percent ZrO_2) is a co-product of copper, phosphate, and iron operations. The material is fused in an electric furnace, then crushed, ground, and classified. This product is applied as a thermal coating on refractory products. Measurements reported by Hendricks indicate that Ra-226 concentrations in ore were approximately 200 pCi/g, while the product itself (as a fine powder) was much higher, at 1,900 pCi/g (CRC87). Hendricks pointed out that the direct chlorination of zircon puts the radium in the highly soluble radium chloride chemical form, which yields very high leachate concentrations in liquid waste streams (CRC87). In one plant, with radium ore concentrations at 100 pCi/g, the Ra-226 concentration in water under the chlorinator residue pile were noted to be 45,000 pCi/L. The high solubility and mobility of radium chloride presents an potential threat to the environment.

As with the other metals, there is insufficient information with which to reach any conclusions about typical NORM concentrations, other than knowing that this segment does sometimes produce wastes with elevated levels of naturally-occurring radioactivity. Additional investigations are required in order to better characterize this segment of the metal mining and processing industry. No information on zirconium processing waste is contained in the EPA's report to Congress on mineral processing wastes.

7.2.8 Ferrous Metals (Iron and Carbon Steel)

Iron blast furnaces use beneficiated iron ore to produce molten iron that can be cast into products, but is primarily used as the mineral feedstock for steel production. Steel furnaces produce a molten steel that can be cast, forged, rolled, or alloyed in the production of a variety of materials. On a tonnage basis, about nine-tenths of the metal consumed in the U.S. is iron or steel. Iron and steel are used in the manufacture of transportation vehicles, machinery, pipes and tanks, cans and containers, and the construction of buildings, roadway superstructures, and bridges.

Iron and steel are produced at 28 active ferrous metal facilities located in 10 states throughout the U.S. Twenty-one of these facilities are located in five states (Ohio, Pennsylvania, Indiana, Illinois, and Michigan) that are situated around the Great Lakes, with access to lake transport of beneficiated iron ore. The locations and types of operations at these facilities are shown in Table B.7-8. At 26 facilities, both iron and steel are produced. One facility makes only iron and one makes only steel.

Iron is produced either by blast furnaces or by one of several direct reduction processes; blast furnaces, however, account for over 98 percent of total domestic iron production. The modern blast furnace consists of a refractory-lined steel shaft in which a charge is continuously added to the top through a gas seal. The charge consists primarily of iron ore, sinter, or pellets; coke; and limestone or dolomite. Iron and steel scrap may be added in small amounts. Near the bottom of the furnace, preheated air is blown in. The coke is combusted to produce carbon monoxide, the iron ore is reduced to iron by the carbon monoxide, and the silica and alumina in the ore and coke ash is fluxed with limestone to form a slag that absorbs much of the sulfur from the charge. Molten iron and slag are

Table B.7-8. Domestic iron and steel producers.
(Source: EPA90)

<u>Owner</u>	<u>Location</u>	<u>Type of Operation</u>
Acme	Riverdale, IL	Iron; BOF Steel ^a
Allegheny	Brackenridge, PA	BOF Steel
Armco	Ashland, KY	Iron, BOF Steel
Armco	Middletown, OH	Iron; BOF Steel
Bethlehem Steel	Bethlehem, PA	Iron; BOF Steel
Bethlehem Steel	Burns Harbor, IN	Iron; BOF Steel
Bethlehem Steel	Sparrows Point, MD	Iron, BOF, OHF Steel ^b
Geneva	Orem, UT	Iron; OHF Steel
Gulf States Steel	Gadsden, AL	Iron, BOF Steel
Inland Steel	E. Chicago, IN	Iron; BOF Steel
LTV	E. Cleveland, OH	Iron; BOF Steel
LTV	Indiana Harbor, IN	Iron; BOF Steel
LTV	W. Cleveland, OH	Iron, BOF Steel
McLouth Steel	Trenton, MI	Iron; BOF Steel
National Steel	Escore, MI	Iron; BOF Steel
National Steel	Granite City, IL	Iron; BOF Steel
Rouge Steel	Dearborn, MI	Iron; BOF Steel
Sharon Steel	Farrell, PA	Iron; BOF Steel
Shenango	Pittsburgh, PA	Iron
US Steel	Braddock, PA	Iron; BOF Steel
US Steel	Gary, IN	Iron; BOF Steel
US Steel	Fairfield, AL	Iron, BOF Steel
US Steel	Fairland Hills, PA	Iron, OHF Steel
US Steel	Lorain, OH	Iron; BOF Steel
Warren Steel	Warren, OH	Iron, BOF Steel
Weirton Steel	Weirton, WV	Iron; BOF Steel
Wheeling-Pittsburgh Steel	Mingo Junction, OH	Iron; BOF Steel
Wheeling-Pittsburgh Steel	Steubenville, OH	Iron; BOF Steel

a BOF: Basic Oxygen Furnace

b OHF: Open Hearth Furnace

intermittently tapped from the hearth at the bottom. The slag is drawn off and processed. The product, pig iron, is removed, cooled, and transported to steel mills.

All contemporary steelmaking processes convert pig iron, scrap, or direct-reduced iron, or mixtures of these, into steel by a refining process that lowers the carbon and silicon content and removes impurities (mainly phosphorus and sulfur). Three major processes are used for making steel, based on different furnace types: the open hearth furnace (OHF), accounting for 2 to 4 percent of total domestic steel production; the basic oxygen furnace (BOF), with 56 to 59 percent of the total; and the electric arc furnace (EAF) accounting for the remainder. The latter predominantly uses scrap (i.e., non-mineral material) as feed and, therefore, does not contribute to the wastes of interest in this NORM assessment. The open hearth process was prevalent in the U.S. between 1908 and 1969, but its use has diminished. The basic oxygen process has supplanted it as the predominant primary steel-making process.

During the open hearth process, a relatively shallow bath of metal is heated by a flame that passes over the bath from the burners at one end of the furnace while the hot gases resulting from combustion are pulled out the other end. The heat from the exhaust gas is retained in the exhaust system's brick liners. Periodically the direction of the flame is reversed, and air is drawn through what had been the exhaust system; the hot checker-bricks preheat the air before it is used in the combustion in the furnace. Impurities are oxidized during the process and fluxes form a slag which is drawn off and processed or discarded.

The basic oxygen process uses a jet of pure oxygen that is injected into the molten metal by a lance of regulated height in a basic refractory-lined converter. Excess carbon, silicon, and other reactive elements are oxidized during the controlled blows, and fluxes are added to form a slag. This slag is drawn off and processed or discarded.

In all of the iron and steel making operations, as at other smelters, gases from the furnace must be cleaned in order to meet air pollution control requirements. Facilities may use dry collection or wet scrubbers or, as is most often practiced, both types of controls. Large volumes of dust and scrubber sludge are collected and processed or disposed.

Overall primary production of pig iron was steady throughout the latter part of the 1980s, while production of raw steel experienced a steady increase. Between 1985 and 1989,

primary production of pig iron averaged 46 million MT. Production of pig iron in 1989 was 49.1 million MT (68.1 percent of production capacity) (EPA90). Production of raw steel increased from 74 million MT in 1985 to 91 million MT in 1989. The estimated 1988 average capacity utilization rate was 69.5 percent for the basic oxygen furnace and 45.3 percent for the open hearth furnace.

Quantities of slag and air pollution control (APC) dust/sludge generated in 1988 by the 28 facilities listed in Table B.7-8 are summarized in Table B.7-9. The total quantity of slag and APC dust/sludge waste generated by these facilities during 1988 was 34.6 million MT (EPA90). Waste management practices for iron and steel slag include recycling, processing (e.g., crushing and sizing) followed by sale for use as aggregate, and disposal on-site. Waste management practices for APC dust/sludge include disposal on-site and return of the material to the production process via the sinter plant operation.

As shown in Table B.7-9, in 1988 nearly 18.8 million MT of iron blast furnace slag was generated by the processing facilities listed in Table B.7-8. Approximately 14.4 million MT of slag was sold for use in other applications. Distribution of air cooled iron blast furnace slag among its various applications is shown in Table B.7-10. The remaining slag was stored on-site. As of 1988, on-site accumulation of iron blast furnace slag at iron producing facilities totaled over 14.6 million MT, ranging from none to 10 million MT at the different facilities. The facility which has accumulated 10 million MT of slag, Inland Steel in East Chicago, is placing it in Lake Michigan to create land on which additional waste can be deposited.

As shown in Table B.7-9, in 1988 over 13.2 million MT of steel furnace slag was generated by the steel producing facilities listed in Table B.7-8. In 1988, U.S. steel mills recycled approximately 1.8 million MT of steel slag. Over 5.1 million MT was sold for other uses. The remaining 6.3 million MT of steel furnace slag was presumably stockpiled at either the generating facilities or at the slag processing facilities. The distribution of steel furnace slag among its various applications in 1988 is shown in Table B.7-11.

No data on radionuclide concentrations in wastes from ferrous metals production facilities are given in the EPA's report on wastes from mineral processing (EPA90). Using available data on the compositions of slag and APC dust generated during iron and steel production, the EPA determined that concentrations of Ra-226, U-238, and Th-232 in these

Table B 7-9. Special wastes generated by ferrous metals facilities in 1988.
(Source: EPA90)

<u>Waste Types</u>	<u>Amount (million MT)</u>
Iron blast furnace slag	18.8
Iron blast furnace APC dust/sludge ^a	1.2
Steel furnace slag	13.2
Steel furnace APC dust/sludge ^a	1.4

a APC: air pollution control.

**Table B.7-10. Distribution of air-cooled iron blast furnace slag
among its various applications in 1988.
(Source: EPA90)**

Application	Distribution
Road base	57%
Concrete aggregate	12%
Fill	10%
Asphaltic concrete aggregate	7%
Railroad ballast, mineral wool, concrete products, glass manufacture, sewage treatment, roofing, and soil conditioning	14%

Table B.7-11. Distribution of steel furnace slag among its various applications in 1988.
(Source: EPA90)

Application	Distribution
Road base	46%
Fill	25%
Asphaltic concrete aggregate	11%
Railroad ballast, ice control, and soil conditioning	18%

wastes are below screening criteria (5 pCi/g for Ra-226, and 10 pCi/g for U-238 and Th-232). Hence no tests of radionuclide concentrations in iron and steel production wastes are reported in EPA90. Ferrous metals wastes, including mine wastes, tailings, and processing waste constitute the second largest quantity of metal mining and processing wastes (behind wastes from copper production) generated in the U.S. Available information, based on analyses of the chemical compositions of iron ores, indicates that NORM concentrations in these wastes may be very small. However, because precise quantitative information on NORM concentrations in these wastes is lacking, additional investigations are required to better characterize this segment of the metal mining and processing industry.

7.2.9 Lead

Refined lead is produced from ore that comes from mines in Alaska, Idaho, Montana, and Missouri. Processing of this ore is performed at five facilities shown in Table B.7-12.

The primary domestic use of lead is in lead-acid storage batteries. Lead is also used in containers and as an additive for gasoline, although these uses are rapidly declining. Lead is also used to manufacture lead oxides which are used in the battery, ceramics, rubber, and coatings industries. The U.S. Bureau of Mines estimated that after a sharp decline between 1985 and 1986, the quantity of refined lead produced in the U.S. has slowly increased from 370,000 MT in 1986 to 395,000 MT in 1989. The Bureau estimates that primary smelter production will remain at about 400,000 MT in 1990 (EPA90).

Primary lead processing consists of both smelting (blast furnace and dross furnace operations) and refining. In the smelting process sintered ore concentrate is introduced into a blast furnace along with coke, limestone, and other fluxing materials. The lead is reduced, and the resulting molten material separates into four layers: lead bullion (98 wt. percent lead); "speiss" and "matte", two distinct layers of material that contain recoverable concentrations of copper, zinc, and other metals; and blast furnace slag. The lead bullion is then drossed (i.e., agitated in a drossing kettle and cooled to just above its freezing point) to remove lead and other metal oxides which solidify and float on the molten lead bullion. The speiss and matte are sold to copper smelters for the recovery of copper and precious metals. The blast furnace slag is stored in piles and partially recycled or disposed.

Table I .7-12. Primary lead processing facilities in the U.S.
(Source: EPA90)

<u>Operator/Owner</u>	<u>Location</u>	<u>Type of Operation</u>
ASARCO	East Helena, MT	Smelter
ASARCO	Glover, MO	Smelter and Refinery
ASARCO	Omaha, NE	Refinery
Doe Run/Fluor Corp.	Boss, MO	Smelter and Refinery
Doe Run/Fluor Corp.	Herculaneum, MO	Smelter and Refinery

Lead refining operations continue the process of removing various saleable metals from the lead bullion. In the final refining step the bullion is mixed with fluxes to remove remaining calcium, magnesium, and oxide impurities. Reagents such as caustic soda or nitrates may be added to the molten bullion, which is then cooled, causing the impurities to rise to the surface for removal. This refinery residue is returned directly to the blast furnace at the Missouri facilities which involve integrated smelter/refinery operations. The refinery slag at the Nebraska facility is discarded as solid waste. The EPA estimates the long-term annual waste generation rate to be about 469,000 MT per year from lead processing (EPA90). The predominant waste management practice at the five lead facilities is to return a majority of the furnace slag to the sinter plant and stockpile the remainder. The total volume of slag accumulated on-site at the four lead smelting facilities is approximately 2.7 million MT, with quantities ranging from 430,000 MT to 1.36 million MT at the four smelters. The Omaha refinery sends its slag off-site to a landfill.

The slag piles at the four smelting facilities range in area from 20,200 square meters to 48,500 square meters and in height from 6 to 18 meters. The average dimensions of the slag piles are 30,300 square meters and 10.5 meters high.

Lead slag has been used as an aggregate in asphalt to resurface roads. The slag has been shown to have desirable anti-skid and wear resistant properties. It was used as an asphalt aggregate in eastern Missouri for a number of years in the 1970s. The Missouri State Highway Commission also made limited use of lead slag in asphalt mixtures to patch and seal roads in the winter. In Idaho, granulated lead slag was used as an aggregate in asphalt to pave Interstate Route 90. The EPA, however, has found no information indicating that lead slag is currently used as an aggregate in asphalt road paving (EPA90).

Several other potential uses of lead slag are described in the EPA's report on special wastes from mineral processing. It has been shown that finely ground lead slag can be used to replace up to 25 percent of the Portland cement in steam cured blocks without significant loss in block strength. In Idaho, granulated slag from the Bunker Hill smelter in Kellogg, Idaho (now closed) was used as a frost barrier under slabs of concrete and asphalt, as well as bedding material for buried pipelines. Lead slag has been used as an air-blasting

abrasive. Valley Materials Corporation in Midvale, Utah is processing (sizing) lead slag for use as a railroad ballast.

No information on radionuclide concentrations in lead slag is given in the EPA's report on special wastes from mineral processing.

7.3 MINERAL PROCESSING WASTE GENERATION

7.3.1 Mineral Processing Waste Production

The total solid material handled at all surface and underground mines in the U.S. in 1986 was 2,385 million metric tons (MT). Of this, metal mines handled 989 million MT (DOI87). Table B.7-13 presents the approximate distribution of this solid bulk material reported for 1980. The distribution shown in Table B.7-13 is believed also to be representative of current mining wastes generation practices.

A review of the volumes of mine waste and tailings generation reveals that almost 90 percent of the bulk material is from copper and iron ore. The principal mining states for copper and iron are Arizona and Minnesota, respectively. Since waste management and disposal are performed locally, the majority of the wastes and other bulk materials from the metal mining and processing industry remain at the point of generation. However, depending on the mineral, a significant portion of the residual material (i.e., the raw ore) may be shipped for further processing or use at other locations, typically away from the mines.

Estimated slag volumes generated in 1988 from smelting and refining raw ores to produce primary metals are shown in Table B.7-14, summarized from the information presented previously in this chapter. The total slag volume is about a factor of 20 smaller than the volume of mine wastes and tailings shown in Table B.7-13. Slag from ferrous metals production represents about 80 percent of the total slag volume produced by smelting and refining raw ores, and copper slag represents almost 10 percent of the total.

Table B.7-13. Estimated amount of waste generated by the mining and beneficiation of metal ores in 1980.^a

Mining Sector	Quantity of Waste (million MT)		
	Mine Wastes	Tailings	Total
Copper	282	241	523
Gold	25	10	35
Iron Ore	200	150	350
Lead	1	10	11
Molybdenum	15	31	46
Silver	10	3	13
Zinc	1	5	6
Other metals ^b	24	5	29
Total:	558	455	1,013

a Data extracted from EPA85, Table 2-10.

b Includes antimony, bauxite, beryllium, magniferous ore, mercury, platinum, rare earths, tin, tungsten, and vanadium.

Table B.7-14. Estimated slag volumes generated during 1988 from processing raw ores to produce primary metals.^a

<u>Metal</u>	<u>Slag Volume (million MT)</u>
Aluminum	2.8
Copper	4.0
Zinc	0.2
Titanium	0.4
Ferrous Metals	34.6
Lead	0.5
Other Metals ^b	1.0
Total	43.5

a Summarized from information presented in this chapter.

b Estimate for other metals such as gold, silver, mercury, platinum, tin, tungsten, zirconium, etc., for which information is not given in this report.

7.3.2 Utilization and Disposal of Bulk Waste Materials

Mine wastes, such as tailings, and heap and dump leachate piles, are managed in a variety of ways. Mining wastes may be used on or off site, disposed of in waste piles, or used in leach operations to recover additional valuable constituents from the ore or tailings still present after milling processes have been completed. A small portion of the waste (less than 10 percent) has been used as backfill or for some offsite uses. Table B.7-15 presents a partial summary of the offsite use of bulk waste material associated with the metal mining industry.

Offsite uses of mine waste tailings include the manufacturing of wallboards, anti-skid products, use in making various construction aggregates, and use as fill or road base. The most common use includes the production of concrete and bituminous aggregates for road construction, in which such wastes are incorporated as an additive. Other applications in road construction include the use of these wastes in road bases, in embankments, and to make anti-skid surfaces. Taconite tailings have proved to be useful when applied as thin (less than 25 mm) road surface overlays because they greatly enhance skid resistance.

Approximately half of the zinc tailings generated in Tennessee are sold for aggregate production. Tennessee zinc tailings are also used as a substitute for mortar or agriculture limestone, with nearly 40 percent being sold for these purposes. Tailings from mills processing ores in New York and the Rocky Mountain states are not suitable as soil supplements because as they have lower concentrations of calcium carbonate and higher concentrations of lead and cadmium. Similar concerns constrain the use of lead tailings in Missouri.

Tailings from molybdenum mining operations have been used in asphalt mixes to resurface roads and parking lots. Gold and silver tailings, in the form of sand and gravel, have been mixed with cement to form concrete for road construction. Lead, zinc, and iron ore tailings have been used for both concrete and bituminous aggregates. Mixtures of crushed waste rock, including waste material from copper, iron ore, lead, gold, and silver mines, have been used in embankments, as backfills, or as pavement bases for many highways. Depending upon the final use, topsoil covers have been placed over fills and embankments made with these materials to control erosion and permit vegetative growth.

Table B.7-15. Uses of mine waste and tailings.^a

<u>Material and Use</u>	<u>Types of Applications^b</u>					
	<u>Copper</u>	<u>Gold & Silver</u>	<u>Iron Ore & Taconite</u>	<u>Lead</u>	<u>Molybdenum</u>	<u>Zinc</u>
Soil supplement						1
Wall board	1	1	1			
Brick and block			3			
Anti-skid products			3			
Embankments	3	3	3	3		
General aggregate		3	3	3		
Fill or pavement base	3	3	3	3		
Asphalt aggregate				3	3	3
Concrete aggregate		3	3	3		3

a Data extracted from SCA88.

b Application codes:

1. Bench-scale research project.
2. Full-scale demonstration project.
3. Full-scale, sporadically practiced.

The use of tailings to produce bricks, blocks, and ceramic products is still at the bench-scale research stage. Copper mill tailings can be used in brick production if pyrites are first removed. Lightweight blocks made from taconite tailings have good structural characteristics, but have not been marketed. However, mining wastes are competitive only when they can be marketed or used in the geographical area close to the point of generation. The costs of handling, and of transportation over large distances, more than offset their low cost and large supply. As a result, the use of such mining wastes does not and will not keep pace with the 1 billion metric tons that are generated each year. Accordingly, a large portion of mining wastes and tailings are disposed in impoundment facilities near the mines and mills where they are produced.

Actual or potential uses of slag tailings generated from smelting and refining raw ores to produce primary metals are shown in Table B.7-16, summarized from the information presented previously in this chapter. Major uses include aggregate in the production of asphalt and concrete, as railroad ballast, and as anti-skid material.

7.3.3 Twenty-Year Waste Generation Estimates

In 1986, metal mines generated approximately 1 billion MT of wastes, of which 300 million MT consisted of tailings. Over the last 20 years, the production of wastes from mineral processing plants has increased somewhat, but this increase may not necessarily reflect an industry-wide trend. For example, some segments of the industry may experience growth while others may see a downturn. The net effect, in the aggregate, is that there may not be any significant changes. Accordingly, a reasonable approach is one which assumes a nearly constant waste production rate of about 1 billion MT per year, yielding a 20 billion MT inventory for the next 20 years. This would result in a 20-year production of 6 billion MT of tailings.

This estimate is somewhat speculative since the mineral mining industry is not fully represented in this report and there is not enough information to completely characterize those NORM waste sectors that are discussed. The extent to which additional sectors would add to the proposed total 20-year inventory is unknown at this point. As with most U.S.

Table B.7-16. Uses of mineral processing slag.^a

Use	Mineral			
	Copper	Zinc	Ferrous Metals	Lead
Asphalt Aggregate	X	X	X	X
Concrete Aggregate	X		X	
Fill	X		X	
Railroad Ballast	X	X	X	X
Road Base		X	X	
Anti-Skid Products	X	X	X	X
Brick and Block				X
Soil Supplement			X	
Pipe Bedding	X			X
Air Blasting Abrasive				X

a Summarized from information presented in this chapter.

ndustry, the mineral mining and processing sector is also subject to competitive forces and the installation of additional productive capacity by foreign concerns. It is not known to what extent the U.S. industry has attempted to adjust in response to foreign competitors. Finally, the use of mining waste in a variety of productive applications is not likely to impact future waste inventories since the development and implementation of new applications will not keep pace with the 1 billion metric tons that are generated each year.

7.4 RADIOLOGICAL PROPERTIES OF MINERAL PROCESSING WASTES

7.4.1 Radionuclide Concentrations

From the limited amount of data available that characterize mineral tailings and wastes, it appears that the ores, tailings, and residues from different metal mining and processing industries possess widely different radiological properties. Except for tailings from the uranium and phosphate rock mining industries (which are discussed separately in preceding sections), the concentrations of uranium and thorium, including their decay products, in mineral processing wastes and tailings have not been widely evaluated. Based on limited data, it appears that ores and tailings of most of the metal processing industries contain relatively low concentrations of radium-226, typically less than a few pCi/g. However, it also appears that some metal ores may contain elevated levels of uranium and thorium which require further characterization.

This is particularly true for titanium and zirconium and its subsequent processing and for copper ores. The tailings and residues of the industries that process rare earths, such as monazite (rare metals and thorium), zircon sands (zirconium), columbium and tantalum, and the titanium ores of ilmenite, rutile and leucoxene have been known to have elevated levels of Ra-226. It appears that these elevated radionuclide concentrations are a result of the chemical beneficiation processes employed in these industries.

With the copper mining industry, on the other hand, the potential source of NORM wastes resides in the remaining mining spoils and overburden which are known to be rich

in uranium ores. The presence of U_3O_8 in such waste has been observed at relatively high concentrations and, particularly in copper wastes from Arizona and New Mexico, on the same order of magnitude as those traditionally found in uranium mines. No numerical data on the radiological properties of tailings and wastes from mining iron ores, which represent the second largest volume of metal mining wastes (after copper wastes), could be found for inclusion in this report.

The source term used to assess the risks from mineral processing NORM is shown in Table B.7-17. This source term is representative of radionuclide concentrations reported in this section for titanium and zirconium wastes, and may also be typical of radionuclide concentrations in the tailings from copper mines in the southwestern U.S. The Pb-210 and Po-210 concentrations were estimated by assuming a radon emanation coefficient of 0.3. U-235 was assumed to be present at a concentration of 5 percent that of U-238.

7.4.2 Radon Flux Rates

Other than the information presented above, no readily available data were identified characterizing radon emanation rates from such waste forms. Radon emanation rates may be assumed to be nearly identical to that of typical soils. For example, the NCRP notes that for typical soils, an average radon surface flux rate is about $0.5 \text{ pCi/m}^2\text{-s}$ per pCi/g (NCR87). Given higher Ra-226 concentrations, e.g., 35 pCi/g (see above), the corresponding radon flux rate is estimated to be at least $18 \text{ pCi/m}^2\text{-s}$, other things being equal. It should be noted that this radon flux rate is a very speculative estimate given the varied distribution of these waste forms and their associated physical and chemical properties.

7.4.3 External Radiation Exposure rates

Radiation exposure rates associated with mineral processing wastes are expected to vary from relatively low to significantly higher levels for some of the waste forms known to have elevated radionuclide concentrations. For example, exposure levels as high as several hundred $\mu\text{R/h}$ have been observed from monazite wastes. Depending upon the source of radioactivity, radiation levels may vary significantly because many of the decay products may

Table B.7-17. Radionuclide source term for mineral processing wastes.

<u>Nuclide</u>	<u>Concentration (pCi/g)</u>
Po-210	25.0
Pb-210	25.0
Ra-226	35.0
Ra-228	10.0
Th-228	10.0
Th-230	35.0
Th-232	10.0
U-234	35.0
U-235	1.8
U-238	35.0

no longer be in secular equilibrium with uranium and thorium. This is especially true with concentrates which are subject to chemical extraction since the process may selectively deplete or enrich some of the decay products.

Given the disposal method and the mode of exposure, radionuclides, and source to receptor geometry, it can be assumed that the resulting radiation doses may be scaled up based on empirically derived exposure rate conversion factors for environmental conditions. These conversion factors represent typical soils and include the effects of gamma ray scatter, build-up, and self-absorption (NCR87). This approach is valid for large quantities of waste, which for practical purposes may be assumed to represent an infinite plane or slab source. For example, the conversion factors for the uranium and thorium decay series are 1.82 and 2.2 $\mu\text{R/h}$ per pCi/g , respectively. Assuming a U-238 and Th-232 concentration of 35 and 10 pCi/g , respectively, the total incremental exposure rate is estimated to be about 90 $\mu\text{R/h}$. In the United States, ambient exposure rates due to terrestrial radiation are known to range from 3 to 16 $\mu\text{R/h}$ (NCR87).

7. GENERIC SITE PARAMETERS AND SECTOR SUMMARY

7.1 Generic Mineral Processing Waste Site

The generic site for the metal mining and processing waste risk assessment represents a large mine and mineral processing plant. The generic mine and mill site are assumed to be located in southern Arizona where ore associated with copper, precious metals, and other minerals are believed to have elevated levels of uranium. The model site consists of a commingled waste rock, overburden, and a tailings pile of 50 hectares. The tailings have no known value other than reprocessing for their mineral content. The site is located in an area with an average population density. The pile is approximately squared with dimensions of 700 m by 700 m, with a height of 30 meters. Assuming a density of 2 g/cm^3 , this results in a pile of 30 million MT of tailings, overburden, and wastes. The site is also assumed to be located near a surface stream and the region is underlain with an aquifer.

While there is evidence to believe that certain ores contain quantities of pitchblende, the model mine is based on the assumption that during mining and milling this material is diluted through mixing, with average U-238 and Th-232 (including their decay products) concentrations of 35 pCi/g and 10 pCi/g, respectively. It is difficult to judge the representativeness of these values, except that the data indicate that a portion of the overburden and tailings could contain such levels of naturally-occurring radioactivity.

The September 1989 draft assessment contained an analysis of the risks from a small waste pile with elevated U-238 and Th-232 concentrations assumed to be typical of a few sites in the southwestern U.S. Only a few such sites may exist in isolated locations, and they are not considered representative of mineral processing waste sites. Therefore, the small waste site with higher radionuclide concentrations was not included in this updated analysis.

7.5.2 Population Distribution

The generic site is assumed to be located in a rural area in Arizona. The population density is assumed to be 46 persons per square mile (average for Arizona) (BOC87).

7.5.3 Radionuclide Concentrations

The above discussions revealed that the overburden of ores mined in the U.S. and the slag and tailings from processing these ores do not generally appear to contain elevated levels of naturally-occurring radionuclides. However, some of the residues associated with the processing of both domestic and imported ores, and some of the overburden associated with the copper mining industry, may contain elevated concentrations of radionuclides which could result in increased exposures to the general public. This is especially true for the tailings and residues associated with the processing of minerals, such as monazite, zircon, ilmenite, and rutile. This is also the case for the production of tin, titanium, zirconium, and hafnium. Furthermore, some of these wastes may become dispersed into the environment since they may be used in various applications, e.g., incorporation in roads and building materials or dispersal in agricultural fields.

For this risk assessment the source term is based on a Ra-226 concentration of 35 pCi/g which is representative of radionuclide concentrations reported in this section for tin, titanium, and zirconium wastes and for copper tailings from mines in the southwestern U.S. The members of the U-238 and Th-232 decay series are assumed to be in equilibrium with their uranium and thorium parent nuclides, and the radon emanation coefficient is assumed to be 0.3.

B.7 REFERENCES

- BEA89** Richard Beard, Arizona Department of Mineral Resources, Tucson, AZ, 1989, Personal Communication, Department of Mines and Mineral Resources, Phoenix, AZ.
- BOC87** Bureau of the Census, Statistical Abstract of the United States - 1988, 108th Edition, Department of Commerce, Washington, DC, December 1987.
- BOM90** U.S. Bureau of Mines, Mineral Community Summaries, 1990 edition, p. 191.
- CRC87** NORM in Mineral Processing, by Donald W. Hendricks, 19th Annual National Conference on Radiation Control, May 18-21 1987. Boise, ID, February 1987, Published by Conference of Radiation Control Program Directors, Inc., Frankfort, KY.
- CRC81** Natural Radioactivity Contamination Problems, Report No. 2, August 1981, Published by Conference of Radiation Control Program Directors, Inc., Frankfort, KY.
- DOI89** Minerals and materials, A Bimonthly Survey, February - March 1989, Bureau of Mines, U.S. Department of the Interior, Washington, DC.
- DOI87** Minerals Yearbook, Vol. 1, Metals and Minerals, Bureau of Mines Department of Interior, Washington, DC.
- DOI85** Zirconium and Hafnium, A Chapter from Mineral Facts and Problems, 1985 Edition, United States Department of the Interior, Washington, DC.
- EPA90** Report to Congress on Special Wastes from Mineral Processing, EPA/530-SW-90-070C, July 1990, Office of Solid Waste and Emergency Response, Washington, D.C.
- EPA85** Report to Congress: Wastes from the Extraction and Beneficiation of Metallic Ores, Phosphate Rock, Asbestos, Overburden from Uranium Mining, and Oil Shale, EPA 530-SW-85-033, December 1985, Office of Solid Waste and Emergency Response, Washington, DC.
- EPA83** Evaluation of Management Practices for Mine Solid Waste Storage, Disposal, and Treatment, Vol I, Characterization of Mining Industry Wastes (Draft), U.S. EPA, Resource Extraction and Handling Division, Industrial Environmental Research Laboratory, Office of Research and Development, Cincinnati, OH.
- EPA82a** Emissions of Naturally-Occurring Radioactivity from Aluminum and Copper Facilities, EPA 520/6-82-018, November 1982, Office of Radiation Programs, Las Vegas Facility, Las Vegas, NV.

EPA82b Environmental Protection Agency, Emissions of Naturally Occurring Radioactivity Underground Zinc Mine and Mill, EPA-520/6-82-020, November 1982, Office of Radiation Programs - Las Vegas Facility, U.S. EPA, Las Vegas, Nevada.

EPA79 Performance Evaluation of an Electrostatic Precipitator Installed on a Copper Smelter Reverberatory Furnace, EPA 600/2-119, June 1979, Industrial Pollution Control Division, Industrial Environmental Research Laboratory, Cincinnati, OH.

EPA78a Environmental Assessment: Primary Aluminum, United States Environmental Protection Agency, Industrial Environmental Research Laboratory, Cincinnati, OH, Nov. 1, 1978 (pre-publication copy).

EPA78b Environmental Assessment: Primary Copper, Lead, and Zinc, United States Environmental Protection Agency, Industrial Environmental Research Laboratory, Cincinnati, OH, Nov. 1, 1978 (pre-publication copy).

GRA89 Roy Grosshoff, Private Communication, August 16, 1989, Office of Information, Education, and Administration, Texas Department of Health, Austin, Texas.

HU85 Hu, S.J., Radium-226 and Thorium-232 Concentration in Amang, Health Physics 49, No. 5, p. 1003, 1985.

MCD89 John McDonnell, Roy F. Weston, Inc., Albuquerque, NM, 1989, Personal experience and communication.

NCR87 National Council on Radiation Protection and Measurements, Exposure of the United States Population and Canada from Natural Background Radiation, NCRP Report No. 94, Bethesda, MD, December 1987.

PEI70 Coal, Oil, Natural Gas, Helium, and Uranium in Arizona, by H. Wesley Peirc, S. B. Keith and J.C. Wilt, 1970 Arizona Bureau of Mines Bulletin 18, Available through Arizona Geological Survey, Tucson, AZ.

SCA88 SC&A, Inc. Technical Supplements for the Preliminary Risk Assessment of Diffuse NORM Wastes - Phase I, prepared under U.S. EPA contract N. 68-02-4375, October 1989.

STI62 Still, A.R., Uranium at Copper Cities and other Porphyry Copper Deposits, Miami District, Arizona (unpublished thesis), Harvard University, Cambridge, MA (1962).

USG63 Mineralogy, Internal Structural and Textural Characteristics, and Paragenesis of Uranium-Bearing Veins in the Conterminous United States, by George V. Walker and John W. Adams, 1963, Geological Survey, Professional Paper 455-D.

USG55

Geology and Ore Deposits of the Bagdad Area, Yavapai County Arizona, by C. A. Anderson, E. A. Scholz, and J.D. Strobell, Jr., 1955, Geological Survey Professional Paper 278.

B.8 GEOTHERMAL ENERGY PRODUCTION WASTE

8.1 INTRODUCTION

Geothermal energy can be defined as heat energy stored or produced in the earth. This energy resource includes high-temperature crustal rocks, sediments, volcanic deposits, water, steam, and other gases which occur at accessible depths from the earth's surface, and from which heat can be economically extracted now or in the future. The earth's crust represents an enormous reservoir of thermal energy. The U.S. Geological Survey estimates that about 1.2 million quads (a quad is a unit of heat energy equal to one thousand trillion -- i.e., 10^{15} -- British Thermal Units) of geothermal energy resources exist in the uppermost 10 kilometers of the crust (EPA87).

Geothermal energy resource systems may be classified into four major categories:

- **Hot igneous systems** - created by the buoyant rise of molten rock (magma) from deep in the crust. In hot igneous systems, the rock is either completely or partly molten (temperature greater than 650°C).
- **Hot dry rock systems** - heated impermeable rock that may or may not have been molten at one time (temperature less than 650°C).
- **Geopressured systems** - characterized by the presence of hot fluids under high pressure, containing dissolved hydrocarbons, usually found in deep sedimentary basins with a low level of compaction and a relatively impermeable caprock. These systems reach moderately elevated temperatures (temperature 90° to 200°C).
- **Hydrothermal systems** - usually found in porous sedimentary rock or in fractured rock systems, such as volcanic formations. The two classes are vapor-dominated systems, which contain mostly steam (temperature 180° to 200°C), and liquid-dominated systems (temperature 30° to 350°C).

The first three categories contain the most heat energy, but the technology does not yet exist to exploit them. Current research is aimed at removing the technological barriers that prevent the development of these resources.

The technology exists to economically extract energy from the fourth category, hydrothermal systems. Hydrothermal systems consist of high-temperature water and/or steam trapped in porous and permeable rock reservoirs. The heat available in the geothermal rock reservoirs is exploited by means of wells that bring hot water and/or steam to the surface. Identified hydrothermal systems with temperatures greater than or equal to 90°C are located mostly in the western U.S. -- primarily in the states of California, Oregon, and Nevada.

The utilization of geothermal energy requires drillholes for the withdrawal of high temperature fluids from the ground, surface utilization equipment (e.g., steam turbines or heat exchangers and associated fluid handling equipment), and a fluid disposal system (e.g., percolation ponds or reinjection wells). At each stage of the geothermal utilization process, the natural hydrothermal fluids, which may have been at thermal and chemical equilibrium with the rocks and minerals in the geothermal reservoir, can experience substantial changes in temperature, pressure, and pH values. These changes can affect the solubility of the various dissolved minerals in the hydrothermal fluids, causing these minerals to precipitate out and form scale or sludge on the inside surfaces of the equipment used to extract and utilize the steam and briny liquids that constitute the geothermal resource.

As is the case for geological formations from which oil and natural gas are obtained (see Section B.5), both uranium and thorium and their radioactive daughters may be present in underground formations from which geothermal fluids are extracted. Uranium and thorium are highly insoluble; however, radium is slightly soluble and may be brought to the surface and deposited with the scale or sludge that coats the inside surfaces of geothermal energy production systems. The concentrations of NORM in geothermal wastes will vary with the nature and location of the geothermal resource and with the physical and chemical changes that take place as this resource is extracted and utilized.

Geothermal energy currently makes a relatively minor contribution to total energy production in the U.S. Most of the effort in characterizing the wastes from utilization of this resource has been directed at identifying the chemical properties of these wastes, including the chemical species, corrosivity, and chemical toxicity. Only very limited attention has been paid to characterizing the radiological properties. Consequently, the radiological hazards are not well understood, and only limited data on NORM concentrations are available. The EPA

has published a report to Congress on the management of wastes from geothermal energy (EPA87) which includes some information on radium concentrations in geothermal wastes. An Environmental Impact Report prepared in support of an application for a monofill disposal facility for wastes from a liquid-dominated system in California's Imperial Valley (ERC90) includes some radium concentration data for these wastes. Additional studies are needed to adequately characterize the radioactive properties of geothermal wastes.

In the following sections, descriptions are provided of the geothermal energy industry and of the properties of geothermal wastes. Also provided are projections of the quantities of waste that might be produced by this NORM sector. This information is used to assess potential exposures and health impacts to members of the general public and critical population groups. A radiological risk assessment is performed (see Chapter D) assuming that both exposed populations reside near a generic site.

8.2 OVERVIEW OF THE GEOTHERMAL ENERGY INDUSTRY

Geothermal energy is currently used in the U.S. in two commercial applications: production of electrical power and as a direct source of heat. An indication of the extent of geothermal resource development and use can be obtained by examining data on recent geothermal well drilling operations. Table B.8-1 presents data on the locations of geothermal drilling activities in the U.S. during the years 1981 through 1985 (WIL86). The numbers of wells include both exploratory wells drilled to confirm the existence and determine the extent of the geothermal resource, and wells drilled for development and use. Thermal gradient holes, which are holes drilled to measure the temperature profile, are not included in the tabulation. As shown in the table, California has, by far, the most geothermal development activity. The Geysers, in Sonoma County in northern California, and the Imperial Valley in southern California are the primary development sites.

Table B.8-1. Summary of geothermal drilling activity by state from 1981 to 1985. (Source: WIL86)

State	Number of Wells					Totals
	1981	1982	1983	1984	1985	
Alaska	--	4	--	--	--	4
California	55	67	47	88	64	321
Colorado	1	--	--	--	--	1
Hawaii	2	1	--	--	--	3
Idaho	6	--	3	--	--	9
Louisiana	1	--	--	--	--	1
Montana	--	1	1	--	--	2
Nevada	14	2	4	3	3	26
New Mexico	6	3	3	--	--	12
New York	--	1	--	--	--	1
Oregon	3	--	1	--	1	5
Texas	--	1	1	--	--	2
Utah	--	2	1	2	--	5
Washington	2	1	--	--	--	3
Totals	90	83	61	93	68	395

8.2.1 Electrical Power Production

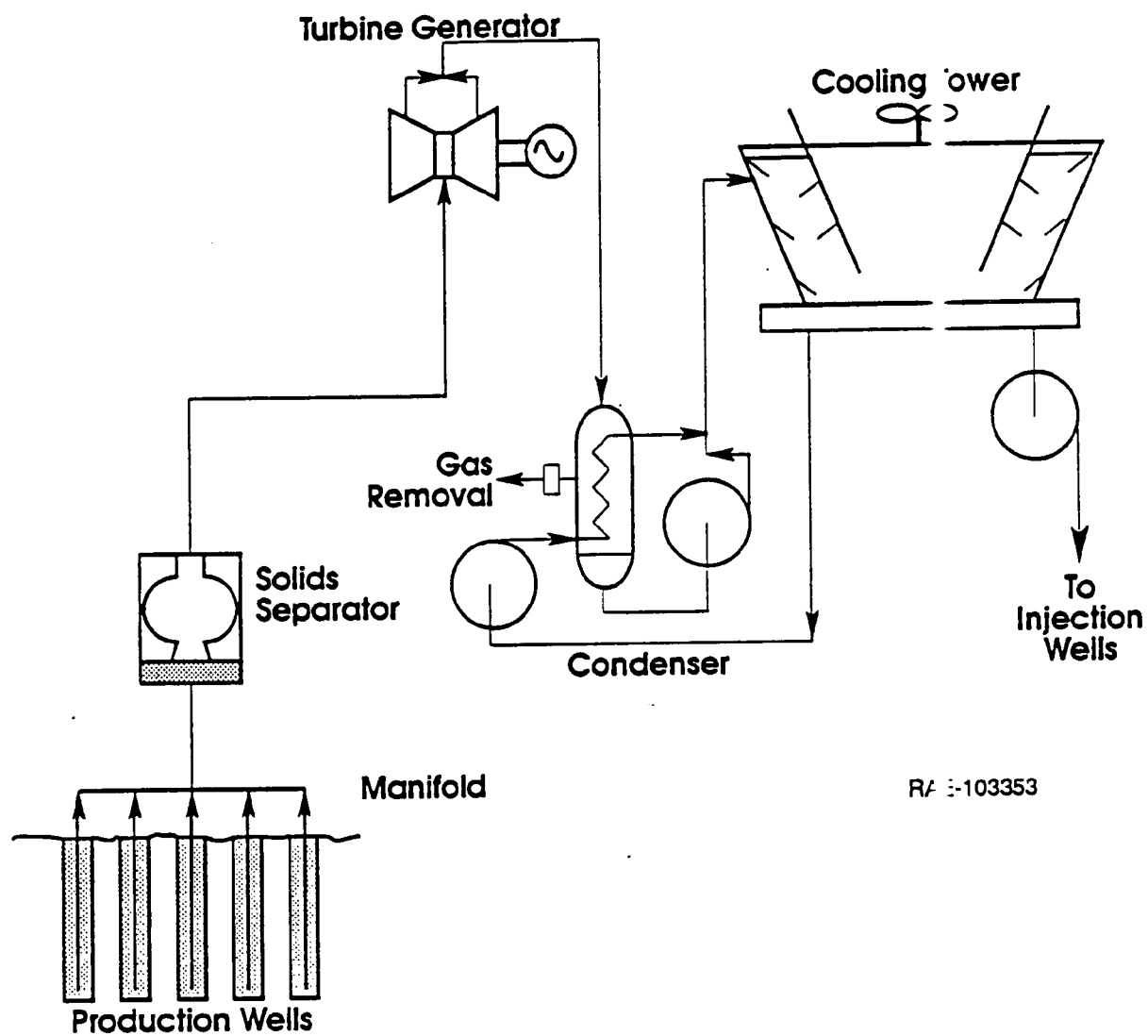
Economically viable methods exist for producing electrical power from either vapor-dominated or liquid-dominated hydrothermal systems. In vapor-dominated systems the high temperature steam can be used directly to turn a turbine-generator and produce electricity. In liquid-dominated systems, hot saline waters (the brine) can transfer heat to a secondary working fluid or can be converted to steam by a flashing process.

In a vapor-dominated system, electrical power is generated using a conventional steam cycle (Figure B.8-1). Typically, 10 to 14 wells are required for a 50-megawatt plant. The production wells are connected to a gathering system (manifold), and steam from the wells provides direct power to drive the turbine generator. A separator is located on the main steam line to remove solids from the steam prior to entry into the turbine. The exhaust steam from the turbine is condensed in a cooling tower which also acts as a concentrating unit for dissolved solids in the condensate. Some condensate is re-used as a cooling medium. Excess condensate is processed to remove suspended solids and is then injected back into the geothermal reservoir. The sludge is dewatered and the resulting filter cake is stored or disposed in accordance with applicable state regulations.

The Geysers in California is the largest vapor-dominated geothermal electrical generating complex in the world. As of 1987, 24 plants were in operation with a combined generating capacity of about 1,800 megawatts (EPA87).

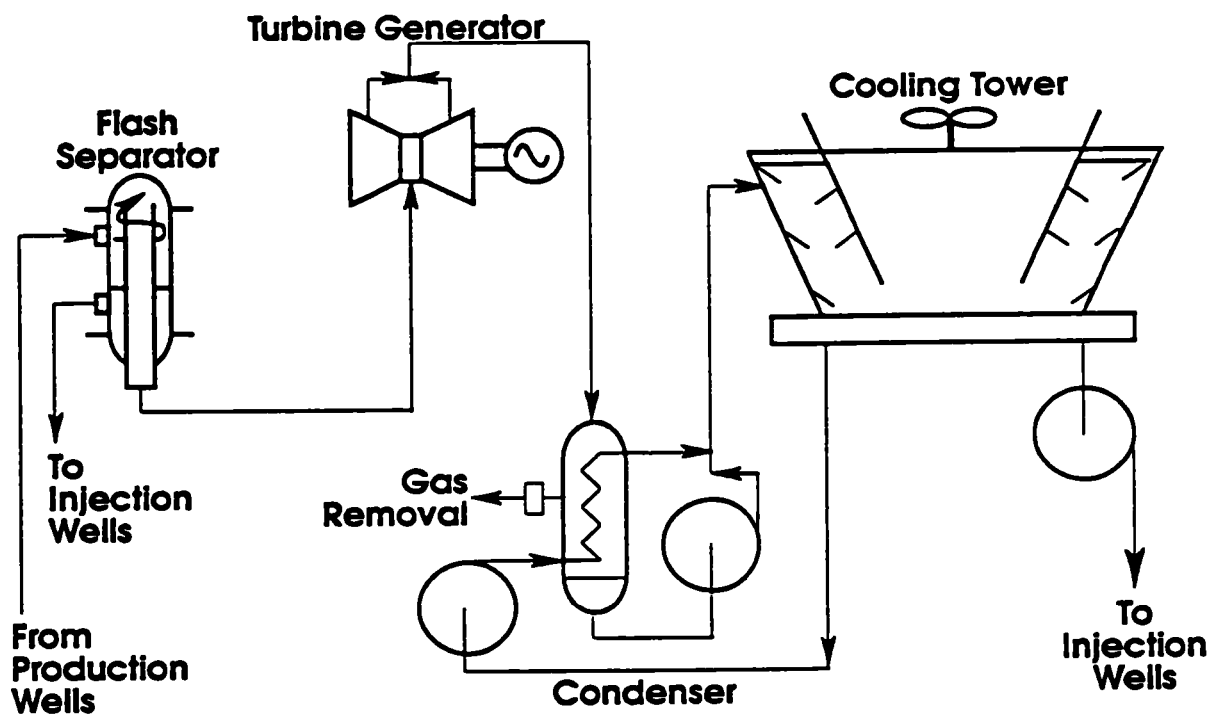
Electricity is produced from liquid-dominated reservoirs by using either of two processes: the flash process and the binary process. Schematics of these processes are shown in Figures B.8-2 and B.8-3.

In the flash process, the geothermal brine is "flashed" to produce steam. The flash process is the partial evaporation to steam of the hot liquid brine by the sudden reduction of pressure in the system. The steam is fed directly to the turbine, with subsequent usage and disposal as described above for vapor-dominated systems. Several power plants in California's Imperial Valley that extract energy from liquid-dominated systems use a flashing process to generate electricity.



RA 3-103353

Figure B.8-1. Schematic of electric power production from a vapor-dominated system.



RAE-103355

Figure B.8-2. Schematic of flashed-steam process for producing electric power from a liquid-dominated system.

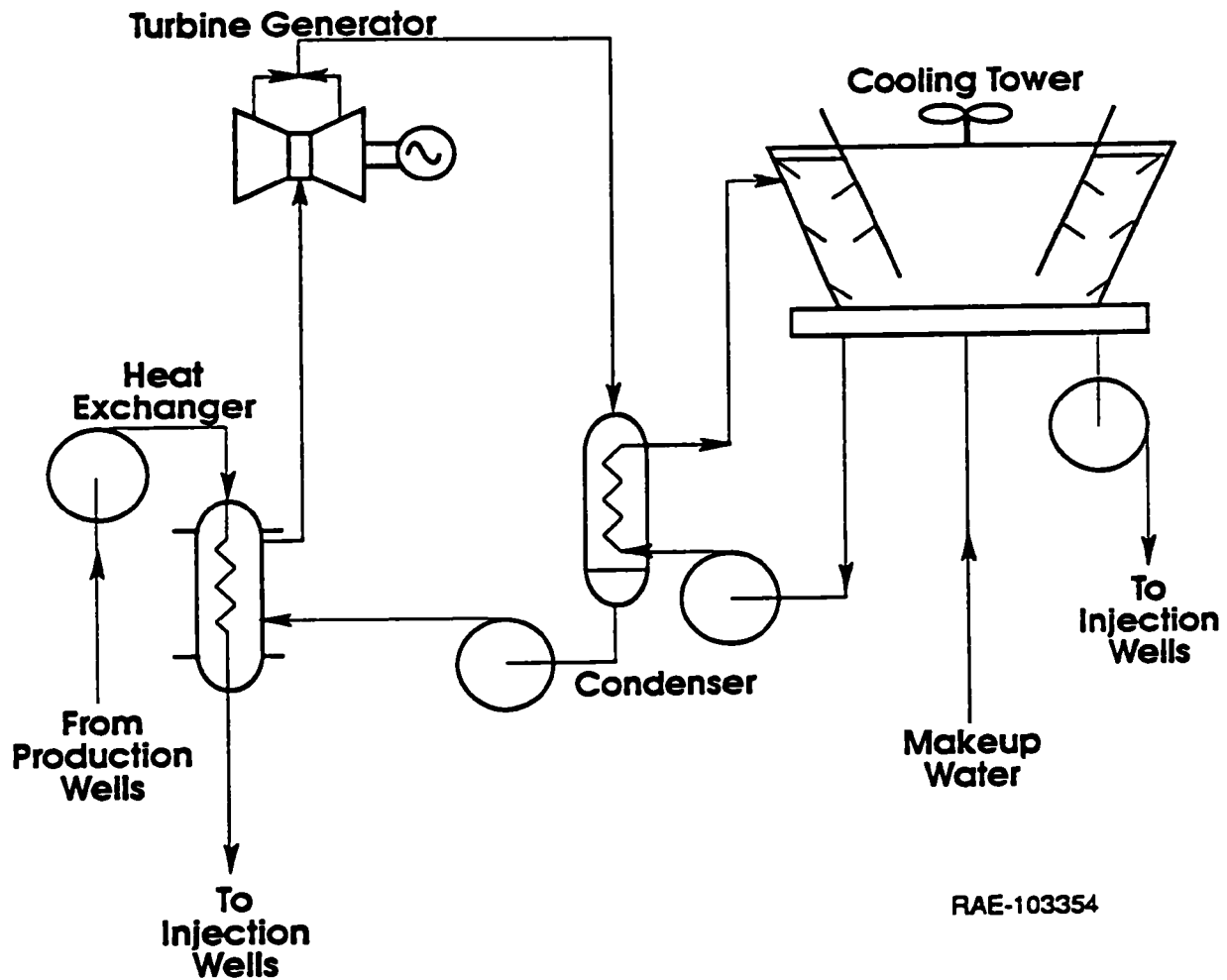


Figure B.8-3. Schematic of binary process for producing electric power from a liquid-dominated system.

In the binary process, the hot brine transfers heat to a working fluid which then expands through the turbine and drives the electric generator. The Heber Demonstration Plant in California's Imperial Valley is the largest binary power plant in the world. This plant uses a binary conversion process consisting of three fluid loops: a geothermal loop, a hydrocarbon working-fluid loop, and a cooling water loop. In the heat exchanger, the brine and hydrocarbon are contained in separate closed loops, allowing no direct contact between loops. The hydrocarbon vapor expands through the turbine which drives the generator. Spent brine is injected back into the geothermal reservoir. The brine temperature must be maintained above 65°C to restrict precipitation of dissolved solids during injection.

Even though the total production of electrical power from geothermal sources in the U.S. remains small, a significant increase in geothermal power production occurred in the decade between 1980 and 1990. At the close of 1986, 2,000 megawatts of geothermal generating capacity were available in the U.S. (GEO87). At the close of 1989, the total geothermal generating capacity had risen to 2,500 megawatts (GEO90). Table B.8-2 lists 29 geothermal power facility sites that were either operating or under construction in the U.S. in 1987 (EPA87). These sites had a combined generating capacity of almost 2,600 megawatts. A "site" is defined as either a single power plant or a multiple operating unit. For example, power-generating facilities at The Geysers are shown as seven sites, although these sites contain more than 25 operating units, owned by different power companies.

Table B.8-2 shows that geothermal power plants are typically small, of the order of a few tens of megawatts. In 1987, California had approximately 96 percent of the total geothermal electrical capacity in the U.S. The remaining four percent was located in other western states and Hawaii. In 1987, approximately 85 percent of the total generating capacity in the U.S. came from vapor-dominated facilities at The Geysers in northern California.

8.2.2 Direct Use of Geothermal Energy

In some areas of the country it has been found efficient and economical to use geothermal energy as a direct source of heat. Sites that have made direct use of geothermal heat are widespread but are located mostly in the western U.S., in the states of California,

Table B.8-2. Geothermal plants for electricity generation (Source: EPA87)

Name	Owner	State/ County	Process Type	Electrical Capacity (MW)	Status^a
East Mesa	Ormat	CA/Imperial	LPB	12.0	UC
East Mesa	Ormat	CA/Imperial	LPB	24.0	OP
East Mesa	Magma Power Co.	CA/Imperial	LPB	12.5	OP
Heber	Heber Geothermal Co.	CA/Imperial	LPF	47.0	OP
Heber	SDG&E Binary Demo	CA/Imperial	LPB	45.0	OP
Salton Sea	Unocal	CA/Imperial	LPF	15.0	OP
Salton Sea (Vulcan)	Magma Power Co.	CA/Imperial	LPF	34.5	OP
Coso	California Energy Co.	CA/Inyo	LPF	25.0	OP
Wendell-Amedee	Geoproducts	CA/Lassen	LPH	20.0	UC
Wendell-Amedee	Wineagle Developer	CA/Lassen	LPB	0.6	OP
Mono Long Valley	Mammoth Pacific	CA/Mono	LPB	7.0	OP
The Geysers	Pacific Gas & Electric	CA/Sonoma	VPS	1560.0	OP
The Geysers	Sacramento Municipal Utility District	CA/Sonoma	VPS	72.0	OP
The Geysers	Northern California Power	CA/Sonoma	VPS	220.0	OP
The Geysers	California Department of Water Resources	CA/Sonoma	VPS	55.0	OP
The Geysers	Freeport Macmoran	CA/Sonoma	VPS	80.0	OP
The Geysers	Santa Fe Geothermal	CA/Sonoma	VPS	80.0	OP
The Geysers	Copa	CA/Sonoma	VPS	150.0	UC
Puna No. 1	Helco	HI/Hawaii Island	LPF	3.0	OP
Lighting Dock	Burgett Floral	NM/Hidalgo	LPB	0.9	OP
Brady Hazen	Chevron	NV/Churchill	LPB	8.3	OP
Dixie Valley - Oxbow	Oxbow Geothermal	NV/Churchill	LPF	50.0	UC
Fish Lake	Steam Reserve Corp.	NV/Esmeralda	LPB	15.0	UC

Table B.8-2. (Continued)

<u>Name</u>	<u>Owner</u>	<u>State/ County</u>	<u>Process Type</u>	<u>Electrical Capacity (MW)</u>	<u>Status^a</u>
Beowawe	Crescent Valley Geothermal	NV/Lander- Eureka	LPF	17.0	OP
Wabuska Hot Springs	Tad's Enterprises	NV/Lyon	LPB	0.6	OP
Desert Peak	Chevron/Sierra Pacific Power Co.	NV/Reno	LPF	9.0	OP
Steamboat Springs	Geothermal Development Association	NV/Washoe	LPB	5.4	OP
Cove Fort - Sulphurdale	City of Provo	UT/Beaver	LPB	4.7	OP
Roosevelt Hot Springs	Utah Power & Light	UT/Beaver	LPF	20.0	OP

a. Status as of 1987.

<u>Key for Process Type</u>			
<u>First Letter</u>	<u>Second Letter</u>	<u>Third Letter</u>	<u>Status</u>
V - Vapor	P - Power Generation	F - Flash Process	OP - Operating
L - Liquid		B - Binary Process	UC - Construction
		S - Conventional Steam	
		H - Hybrid	

Oregon, Idaho, Nevada, New Mexico, Utah, and Colorado. Geothermal heat has been used for homes, offices, schools, commercial buildings, pools, greenhouses, and fish farms. This heat can be extracted from the condensate from an electrical generating facility or directly from a geothermal production well.

The two most common ways of utilizing geothermal energy as a direct source of heat are through downhole and surface heat exchangers. Some 400 to 500 shallow wells are used for space heating in the Klamath Falls and Klamath Hills, Oregon, geothermal areas (LIE86). These wells provide heat for about 500 homes, offices, commercial buildings, schools, churches, and greenhouses. Typically, well temperatures range from 38°C to 110°C. Most of the wells use downhole heat exchangers, which consist of one- or two-tube loops suspended in the wellbore, in direct contact with the hydrothermal fluid. Downhole exchangers are feasible only where reservoir depths are typically less than 500 feet. Usually, the water inside the heat exchanger cycles thermally, eliminating the need for pumps or for fluid disposal.

Surface exchange systems require extraction of the geothermal fluid from the reservoir and, subsequently, some means of spent fluid or brine disposal. The Pagosa Springs Geothermal District space heating system in Colorado has successfully used low temperature (60°C) geothermal fluid in a surface exchange system to heat public buildings, schools, residences, and commercial establishments at significantly lower cost than with conventional fuels (GOE84).

8.3 GEOTHERMAL ENERGY WASTE

Geothermal energy wastes include wastes from exploration and development of geothermal systems, wastes from electrical power production, and wastes from direct use of geothermal energy.

8.3.1 Exploration and Development Wastes

Well drilling activities from geothermal exploration and development generate large quantities of wastes consisting of discarded drilling muds and residues from drilling mud cleaning processes. Drilling mud is a formulation of clay and chemical additives, such as caustic soda or other materials, in a water base. Solids are removed from used drilling muds by circulation of the mud through equipment such as shale shakers, sand traps, hydrocyclones, and centrifuges. After cleaning, the mud is recycled to the drilling operation and the removed solids are disposed of as waste residue. When drilling is completed, the used muds are discharged to reserve pits for storage or disposal.

8.3.2 Geothermal Power Plant Wastes

Wastes generated from geothermal power production include both liquids and solids. Liquid wastes include excess steam condensate from vapor-dominated systems and spent brines from liquid-dominated systems. In vapor-dominated systems, the exhaust steam from the turbine is condensed and pumped to a cooling tower where it is cooled. Excess condensate is processed to remove suspended solids and then injected back into the geothermal reservoir. Spent brines from liquid-dominated systems are also processed to remove solids and injected back into the geothermal reservoir.

Solid wastes include piping and flash tank scale, sludges from processing of steam condensate to remove solids, separated solids from pre-injection treatment of spent brines, and hydrogen sulfide abatement wastes. The bulk of solid wastes from geothermal power production originate from the treatment of spent brines at liquid-dominated systems. The vapor resources at The Geysers are characterized by a dissolved solids content as low as the parts-per-million level; while the hot saline fluids of the Imperial Valley may have a dissolved solids content approaching 30 wt percent (THO89).

During geothermal power production operations, scale forms in process lines, valves, and turbines as the temperature and pressure are reduced and as the pH of the system changes as a result of the release of carbon dioxide. The scale generally consists of barium, calcium, and strontium salts (carbonates, sulfates, and silicates) and silica. The amount and

composition of this scale depends upon the site's mineralogy and the process used for power production. Especially at liquid-dominated facilities, the scale must be periodically removed to ensure proper operation of the power production equipment. As is the case for oil and gas production scale, geothermal scale may contain small amounts of radium and radium daughters that are coprecipitated with the barium and calcium salts.

Brines produced at flash plants require treatment before injection because of their very high dissolved solids content. One method of treating geothermal brine is to allow precipitation of dissolved solids in spent-brine holding ponds. After sufficient time to allow settling, the clarified liquid can be withdrawn from the end opposite the inlet and injected into the producing reservoir. Solids accumulating in the pond are dredged, dried by evaporation, and disposed of at a State-approved landfill.

Hydrogen sulfide abatement constituents include iron sulfide sludge and iron catalysts used to precipitate hydrogen sulfide; emulsion waste from the froth tank, vanadium catalysts, and elemental sulfur from the peroxide extraction process; and sulfur dioxide and sulfur dioxide diluted with water. In California, these wastes are incinerated or placed in a hazardous waste landfill.

Sufficient data are not available to accurately characterize either the volumes or the NORM concentrations in solid wastes from geothermal energy production. Waste generation information in the literature applies to only a few site-specific cases. Most of the available information is from areas such as The Geysers and the Imperial Valley in California, which have the most commercial activity. Since the characteristics of geothermal wastes relate directly to the geology and mineralogy of a resource area, additional site-specific data are required to more fully characterize geothermal industry wastes.

8.3.3 Waste Generation from Direct Users

The primary waste generated from using geothermal energy as a direct source of heat is the spent geothermal fluid remaining after usable heat has been extracted. In most cases, this fluid is considered to be of high enough quality to allow it to be discharged into nearby

surface water bodies (EPA87). Significant amounts of solid wastes are not produced from using geothermal energy as a direct source of heat.

8.3.4 Twenty-Year Waste Generation Estimate

The only significant NORM-contaminated wastes from utilization of geothermal energy are the solid wastes from geothermal power production. These wastes are primarily piping and flash tank scale and the solid residues from brine treatment at liquid-dominated facilities, such as those in California's Imperial Valley. Because of a scarcity of data, no attempt is made in the EPA's report to Congress on management of wastes from geothermal energy (EPA87) to quantify the solid waste produced at power generation facilities.

For this assessment, the twenty-year waste generation estimate is based on a waste generation rate identified in an Environmental Impact Report for a conditional use permit for monofill disposal of geothermal wastes in Imperial County, California (ERC90). Power plants now operating in Imperial County are estimated to produce approximately 20,000 m³ of geothermal filter cake annually. The assumption is made that waste generation, averaged over the 20-year period, might double as additional plants are brought into operation. Doubling this production rate and multiplying by 20 years results in an estimated 20-year waste volume of 800,000 m³.

8.4 RADIOLOGICAL PROPERTIES OF GEOTHERMAL ENERGY WASTES

8.4.1 Radionuclide Concentrations

This radiological assessment is concerned with the radionuclides in solid waste. The principal solid waste materials of concern are the scale in piping and production equipment and the filter cake produced from treatment of the spent geothermal fluid prior to its reinjection into the producing formation.

As is the case for geological formations from which oil and gas are produced, uranium and thorium and their radioactive daughters may be present in formations from which geothermal fluids are extracted. The available information indicates that significant quantities of uranium and thorium are not dissolved or entrained in the geothermal fluids. This is similar to oil and gas production where NORM appears to be associated primarily with the production water, and radium is essentially the only non-gaseous NORM radionuclide produced. The primary radionuclides that appear to be produced with the geothermal fluids are Ra-226 and Ra-228, from the uranium and thorium decay chains, respectively.

There is very little information available on the concentrations of NORM in geothermal solid waste. In the late 1970s, work was done by the EPA/ORP Las Vegas office and others on radon releases associated with geothermal resource use. However, there apparently has been minimal similar work done on the radionuclides in solid wastes. The only definitive information on concentrations of radionuclides in geothermal solid wastes identified for this assessment is contained in an Environmental Impact Report for a conditional use permit for a monofill in which to dispose of geothermal wastes in Imperial County, California (ERC90). This Environmental Impact Report provides results of the analysis of samples from four geothermal power plants in the Imperial Valley. The concentrations of radium in samples of filter cake from these plants were:

Ra-226:	10 to 254 pCi/g
Ra-228:	9 to 193 pCi/g

The solids are generally separated from the fluid in clarifiers. The lower concentrations were observed in the second clarifiers, when more than one clarifier was sampled. The average, volume weighted, concentrations for the six samples (two samples from two of the plants) were:

Ra-226:	160 pCi/g
Ra-228:	110 pCi/g

The concentrations of the decay products were lower than for the parent radionuclides, indicating that the long half-life decay products were not produced with the geothermal fluid.

The analytical results indicated a Ra-226 emanation coefficient of about 25 percent, Pb-210 and Po-210 concentrations of about 110 pCi/g, and a Th-228 concentration of about 30 pCi/g. The concentrations of the decay products will increase with ingrowth time.

8.4.2 Radon Flux from Geothermal Wastes

The geothermal solid wastes are presumed to be disposed of in landfill type disposal cells of about four hectares. The radon flux from the materials will be a function of the Ra-226 concentration and emanating power, the moisture content of the material, and the porosity. The radon flux was estimated using the RAE radon diffusion code (ROG84). The radon flux from an open cell is estimated to be about 160 pCi/m²-sec, using parameters for material properties from several of the geothermal power facility sites in the arid Imperial Valley. Extensive watering for dust control and placement of a 6-in interim cover reduces the flux to 80 pCi/m²-sec during the operating period. A permanent post-operational cover of about 3 meters placed over the disposed geothermal wastes would reduce the radon flux to less than 20 pCi/m²-sec.

8.4.3 External Radiation Exposure Rates

There will be external gamma exposure associated with both Ra-226 and Ra-228 decay products. There is some exposure in the power plants, but the primary potential for exposure is at the disposal site, prior to placing the cover. The exposures at the power plant sites are controlled through minimizing the accumulation of material and by the geometry of equipment which contains the geothermal waste.

8.5 SUMMARY OF GEOTHERMAL ENERGY NORM SECTOR

8.5.1 Generic Geothermal Solid Waste Disposal Site

The generic geothermal solid waste disposal site is assumed to be located in an arid area in southern California because 95 percent of geothermal electric generating capacity is in the state of California. Most of the solid waste from geothermal power production is produced from liquid-dominated systems located in the Imperial Valley and surrounding areas. Therefore, the risk assessment for this sector is based on the disposal of filter cake from the pre-injection treatment of spent brine at a monofill facility in southern California.

The monofill facility is assumed to contain 400,00 m³ of geothermal solid waste. The designated disposal area occupies 100,000 square meters, with a depth of 4 meters. The completed facility is assumed to incorporate a bottom composite liner consisting of an 80-mil thick high density polyethylene (HDPE) liner over 1 m of compacted clay with a maximum permeability of 10⁻⁷ cm/sec. The completed facility also has a composite cover system consisting of 0.6 m of compacted clay topped by 2.0 m of topsoil. The cover is assumed not to be put in place until the monofill is filled with waste. However, an interim cover of 0.15 m of clay is placed over the waste during operations, typically at the end of each week.

8.5.2 Population Exposure

The population density near and around the site is assumed to be the average for the state of California, at 181 persons per square mile (BOC90). Since the likely location of the disposal facility is a desert region in extreme southern California, the actual population density in the vicinity of the site may be much less than this.

8.5.3 Radionuclide Concentrations

Elevated concentrations of uranium and thorium and their radioactive daughter products are sometimes present in hydrothermal systems from which geothermal fluids are

extracted for use in the generation of electricity. The uranium and thorium are highly insoluble and tend to remain in place in the underground reservoir. However, radium is slightly soluble and may be transported to the surface with the geothermal fluids. As the temperature, pressure, and pH of the fluid system change, radium may coprecipitate with the mineral salts that form a scale on the insides of pipes, valves, and tanks, or it may concentrate in the filter cake from processing the geothermal brine prior to injection back into the reservoir. The concentration of radium in geothermal waste depends on its concentration in the underground hydrothermal system and on the processes by which the geothermal fluid is extracted and utilized in electric power production.

Little data are available to accurately characterize NORM concentrations in solid wastes from geothermal energy production. Since the characteristics of geothermal wastes relate directly to the geology and mineralogy of a resource area, significant variations in radium concentrations may occur. Additional studies are needed to adequately characterize the radioactive properties of this waste. For this risk assessment, radionuclide concentrations in geothermal waste are based on information in an Environmental Impact Statement for a proposed monofill for disposal of geothermal wastes in Imperial County, California (ERC90). A Ra-226 concentration of 160 pCi/g and a Ra-228 concentration of 110 pCi/g are assumed, based on limited data from sampling filter cake from treating brine extracted from liquid-dominated systems in the Imperial Valley. The Pb-210 and Po-210 concentrations are each assumed to be 110 pCi/g, and the Th-228 concentration is assumed to be 30 pCi/g.

Although these values are based on limited information, they are similar to the average concentrations of radium and radium decay products in solid waste from oil and gas production. As previously noted, it appears the chemical and physical conditions for mobilizing NORM in geothermal fluids are similar to that for oil and gas. Therefore, it is reasonable to expect that the average radionuclide concentrations in geothermal waste solids would be similar.

The GSX Laidlaw hazardous waste facility in Imperial County has applied for a permit to construct sole use geothermal waste cells. In the permit application, GSX has specified not to accept geothermal wastes with a radium concentration above 200 pCi/g. Based on the stipulation of this operating condition, it would appear that the concentrations

of 160 pCi/g of Ra-226 and 110 pCi/g of Ra-228 (total 270 pCi/g of radium) conservatively reflect the concentrations of NORM that GSX expects may be present in the geothermal wastes.

REFERENCES

- BOC90 Bureau of Census, Statistical Abstract of the United States - 1990, 110th Edition, Department of Commerce, Washington, D.C., 1990.
- EPA87 Environmental Protection Agency, Report to Congress: Management of Wastes from the Exploration, Development, and Production of Crude Oil, Natural Gas, and Geothermal Energy, Volume 2 of 3, Geothermal Energy, EPA/530-SW-88-003, Office of Solid Waste, December 1987.
- ERC90 ERC Environmental Energy Services Co., Final Environmental Impact Report for General Plan Amendment, Zone Change, and Conditional Use Permit, prepared for County of Imperial Planning Department, 1990.
- GEO87 Wallace, R.H., Jr., and K.L. Schwartz, Geothermal Energy, Geotimes, Vol. 32, No. 2, p. 28, February 1987.
- GEO90 Reed, M.J., Geothermal Energy, Geotimes, Vol. 35, No. 2, p. 24, February 1990.
- GOE84 Georing, S.W., et al., Direct Utilization of Geothermal Energy for Pagosa Springs, Colorado, U.S. Department of Energy, Division of Geothermal and Hydropower Technologies, 1984.
- LIE86 Lienau, L.J., Status of Direct Heat Projects in the Western States, GHC Bulletin, Fall 1986, pp. 3-7.
- NCR75 National Council on Radiation Protection and Measurements, Natural Background Radiation in the United States, NCRP Report No. 45, 1975.
- ROG84 Rogers, V.C., K.K. Nielson, D.R. Kalkwarf, Radon Attenuation Handbook for Uranium Mill Tailings Cover Design, NUREG/CR-3533, RAE-18-5, 1984.
- THO89 Thomas, D.M., and J.S. Gudmundson, Advances in the Study of Solids Deposition in Geothermal Systems, Geothermics, Vol. 18, No. 1/2, pp. 5-15, 1989.
- WIL86 Williams, T. Department of Energy Comments on the Technical Report, "Wastes from Exploration, Development, and Production of Crude Oil, Natural Gas, and Geothermal Energy: An Interim Report on Methodology for Data Collection and Analysis," 1986.

CHAPTER D

RISK ASSESSMENT FOR DIFFUSE NORM

D.1 INTRODUCTION

The results of evaluations of possible health impacts from the storage or disposal of diffuse NORM wastes are presented in this chapter. These evaluations are based on the waste inventories, generic site parameters, and radiological properties of the NORM waste sectors described in Chapter B. Health impacts from the storage or disposal of NORM wastes are estimated for workers at the storage or disposal sites, for onsite individuals, for persons belonging to the critical population group (CPG), and for the general population in the vicinity of the disposal sites.

Workers at the storage and disposal sites include disposal pile workers and office workers. The disposal pile worker is an adult employee who works 2,000 hours per year, spending 80 percent of his time on the waste pile. It is assumed that the waste pile is not covered or capped. The worker uses machinery such as a grader or bulldozer which places him one meter above the pile surface and provides some shielding from direct gamma radiation.

The office worker also works 2,000 hours per year in a building located at the disposal site. While in the building, the worker is exposed via the indoor radon inhalation pathway. Although an office building would likely be located at some distance from the disposal pile, in estimating the indoor radon concentration it is assumed that the building is located on the pile. This results in a conservatively high estimate of the radon dose received by the office worker.

The onsite individual is assumed to live on a site which was formerly used for the disposal of diffuse NORM wastes. Exposures received by this onsite individual include inhalation of radon gas and direct exposure to gamma radiation. For indoor exposure to radon, the exposure fraction (i.e., the fraction of a year the person is exposed) is 0.75. For

direct exposure to gamma radiation the equivalent exposure fraction is 0.5 which takes into account the time spent outside plus the time spent indoors at a reduced exposure level.

The CPG includes those individuals who might be exposed to the highest doses as a result of normal daily activities. For this assessment of the risk from diffuse NORM, the member of the CPG is assumed to be an adult who lives in a house located 100 m from the disposal pile. The person obtains all of his water from a well adjacent to the house. Fifty percent of his foodstuffs are assumed to be grown onsite. Exposure pathways for which possible health impacts are evaluated include direct gamma exposure, downwind exposure to radon gas, inhalation of contaminated dust, and ingestion of contaminated water and foodstuffs.

Several exposure pathways are evaluated for the general population residing near the disposal sites. Population exposures are evaluated for both ingestion and inhalation exposure pathways.

Dose and risk calculations are performed for the following individual and population exposure scenarios:

- **Worker**
 - Direct gamma exposure.
 - Dust inhalation.
 - Indoor radon inhalation.
- **Onsite Individual**
 - Direct gamma exposure.
 - Indoor radon inhalation.
- **Member of CPG**
 - Direct gamma exposure.
 - Inhalation of contaminated dust.
 - Downwind exposure to radon.
 - Exposure to NORM in building materials.
 - Ingestion of drinking water from a contaminated well.
 - Ingestion of foodstuffs contaminated by well water.
 - Ingestion of foodstuffs contaminated by dust deposition.
 - Ingestion of foodstuffs grown on repeatedly fertilized soil.

- **General Population Near Disposal Sites**

- Downwind exposure to resuspended particulates.
- Downwind exposure to radon.
- Ingestion of river water contaminated via the groundwater pathway.
- Ingestion of river water contaminated via surface runoff.
- Ingestion of foodstuffs grown on repeatedly fertilized soil.

The exposure scenarios evaluated for each of the NORM waste sectors described in Chapter B are shown in Table D.1-1.

Health impacts from exposures to diffuse NORM wastes are expressed both in terms of committed dose equivalent (hereafter referred to as dose) and the probability that a fatal cancer might result from exposure. Because the actual duration of an individual's exposure to NORM waste is unknown and may vary depending upon the exposure scenario, all dose and risk calculations are based on one year of exposure. For ingestion and inhalation exposures, the calculated doses are expressed in terms of the 50-year committed dose equivalent (mrem) from one year of exposure. For direct gamma exposure, the dose is expressed in terms of the annual committed whole body dose equivalent (mrem/yr). For all of the exposure pathways, the health effects are expressed in terms of the lifetime (70-year) risk of a fatal cancer from one year of exposure.

The dose calculations are based on the PATHRAE dose assessment methodology (EPA87a) and utilize equations derived from the PATHRAE methodology. The PATHRAE dose assessment model was developed for the EPA to estimate doses to individuals from low-level radioactive wastes disposed in a variety of land disposal settings. Thus, the methodology used for these dose calculations is generally consistent with established EPA models. The exposure models, model assumptions, and input parameter values used for these dose and risk calculations are summarized in Section D.2 of this chapter. The results of these dose and risk calculations are presented in Section D.3.

Table D.1-1. Exposure scenarios for diffuse NORM risk assessment.

Exposure Scenario	Uranium Overburden	Phosphate Waste	Phosphate Fertilizer	Coal Ash	Water Treatment Sludge – Fertilizer	Water Treatment Sludge – Landfill	Mineral Processing Waste	Oil & Gas Scale/Sludge	Geothermal Waste
<u>Worker</u>									
Direct Gamma Exposure	X	X	X	X	X	X	X	X	X
Dust Inhalation	X	X	X	X	X	X	X	X	X
Indoor Radon Inhalation	X	X		X		X	X	X	X
<u>Onsite Individual</u>									
Direct Gamma Exposure	X	X	X	X	X	X	X	X	X
Indoor Radon Inhalation	X	X	X	X	X	X	X	X	X
<u>Member of CPG</u>									
Direct Gamma Exposure	X	X	X	X	X	X	X	X	X
Inhalation of Contaminated Dust	X	X	X	X	X	X	X	X	X
Downwind Exposure to Radon	X	X	X	X	X	X	X	X	X
NORM in Building Materials		X		X			X		
Ingestion of Drinking Water from a Contaminated Well	X	X	X	X	X	X	X	X	X
Ingestion of Foodstuffs Contaminated by Well Water	X	X	X	X	X	X	X	X	X
Ingestion of Foodstuffs Contaminated by Dust Deposition	X	X	X	X	X	X	X	X	X
Ingestion of Foodstuffs Grown on Repeatedly Fertilized Soil			X		X				
<u>General Population Near Disposal Sites</u>									
Downwind Exposure to Resuspended Particulates	X	X	X	X	X	X	X	X	X
Downwind Exposure to Radon	X	X	X	X	X	X	X	X	X
Ingestion of River Water Contaminated Via the Groundwater Pathway	X	X	X	X	X	X	X	X	X
Ingestion of River Water Contaminated by Surface Runoff									
Ingestion of Foodstuffs Grown on Repeatedly Fertilized Soil			X		X				

D.2 RISK ASSESSMENT METHODS

In this section, the exposure scenarios and models used to evaluate health impacts from the storage and disposal of diffuse NORM wastes are described. Assumptions made in using the models to estimate individual and population doses and health effects are discussed. Values of the input parameters used in the dose equations are presented. As already noted, the dose calculations utilize equations derived from the PATHRAE dose assessment methodology. The data used as input parameters comes, in part, from the characterizations contained in Chapter B and from data expressly developed in this chapter.

2.1 THE PATHRAE DOSE ASSESSMENT MODEL

The PATHRAE performance assessment model (EPA87a) was initially developed as an analytical tool to assist the U.S. Environmental Protection Agency in developing standards for low-level radioactive waste and below regulatory concern waste disposal. The PATHRAE model provides estimates of health effects which could potentially occur if radioactive wastes were disposed of in a near surface facility, sanitary landfill, or other geological setting. PATHRAE has been used to calculate effective dose equivalents to members of the critical population group from the disposal of radioactive wastes at sites located in diverse hydrogeologic, climatic, and demographic settings. PATHRAE has also been modified to consider population impacts from airborne exposures (ROG85).

An important advantage of the PATHRAE methodology is its simplicity while still allowing a comprehensive set of radionuclides, disposal settings, and exposure pathways to be analyzed. The effects of changes in disposal site and facility characteristics can be readily investigated with relatively few parameters needed to define the problem.

The PATHRAE methodology models both off-site and on-site pathways through which persons may come in contact with radioactivity from the waste. The off-site pathways include groundwater transport to a well and to a river, surface water transport to a river, and

atmospheric transport. On-site pathways include direct gamma exposure, dust inhalation, and pathways by which post-closure reclaimers or intruders onto a site might become exposed by such activities as building a house and living on a site.

2.2 EXPOSURE SCENARIOS

The following subsections briefly describe each exposure scenario and present all equations derived from PATHRAE methodology. More complete explanations and derivations of the dose equations used in this analysis are contained in the references (EPA87a, ROG85).

2.2.1 Worker – Direct Gamma Exposure

This exposure pathway describes the external gamma radiation dose received by an employee who works at the site where the diffuse NORM waste is being stored or disposed. The employee works at the site 2,000 hours per year, spending 80 percent of his time on the disposal pile. He uses machinery such as a grader or bulldozer which places him about 1 meter above the surface of the pile and provides some shielding from direct gamma radiation. The equation used to calculate the radiation dose to this worker is:

$$D = \frac{C * M}{A} * e^{-\mu_c t_c} * \left(\frac{1 - e^{-\mu_w t_w}}{\mu_w t_w} \right) * f_{wex} * f_{sh} * DFG \quad (D-1)$$

where

- D = Annual dose (mrem/yr)
- C = Nuclide concentration in waste (pCi/g)
- M = Mass of reference waste pile (g)
- A = Plane area of waste pile (m²)
- μ_c = Attenuation coefficient of cover over the waste (m⁻¹)
- t_c = Thickness of cover over the waste (m)
- μ_w = Attenuation coefficient of waste material (m⁻¹)

- t_w = Thickness of waste material (m)
 f_{wex} = Fraction of year the worker is exposed = $(2000/8766)*0.8 = 0.1825$
 f_{sh} = Shielding factor = 0.6
 DFG = External gamma dose conversion factor (mrem/yr per pCi/m²).

Equation D-1 takes into account both the attenuation of gamma radiation by the waste itself and the attenuation provided by cover material (if any) placed over the waste. The f_{sh} term accounts for the reduction in exposure due to shielding provided by the grader or bulldozer used by the worker. Equation D-1 does not include dose buildup factors, because experience with PATHRAE has shown that the use of buildup factors in this formalism overestimates gamma doses.

2.2.2 Worker -- Dust Inhalation

This exposure pathway describes the radiation dose from dust inhaled by the worker at the diffuse NORM storage or disposal site. The equation used to calculate this dose is:

$$D = C * f_{ds} * d_d * U_i * f_{wex} * DF_{inh} \quad (D-2)$$

where

- D = 50-year committed dose equivalent from one year's exposure (mrem)
 C = Nuclide concentration in waste (pCi/g)
 f_{ds} = Soil dilution factor (dimensionless)
 d_d = Dust loading in air breathed (g/m³)
 U_i = Volume of air breathed in a year (m³/yr)
 f_{wex} = Fraction of year the worker is exposed = $(2000/8766)*0.8 = 0.1825$
 DF_{inh} = Inhalation dose conversion factor (mrem/pCi).

2.2.3 Worker -- Indoor Radon Inhalation

This exposure pathway describes the health effects from indoor radon inhalation to an office worker who works inside a building at the NORM storage or disposal site. Although any office building would probably be located adjacent to the disposal pile, the assumption is made that the building is located on top of the pile. This results in a conservatively high estimate of the risk from indoor radon inhalation. The equation used to calculate the health effects from inhalation of radon is:

$$R = \frac{C_R * \rho_w * E * f_{dex}}{h * \lambda_h} * \sqrt{\lambda * D_w} * e^{-(\sqrt{\lambda D_c} * t_b)} * DF_R \quad (D-3)$$

where

- R = Risk from radon inhalation (health effects)
- C_R = Radium concentration in the waste (pCi/g)
- ρ_w = Waste density (g/m^3)
- E = Radon emanation coefficient (dimensionless)
- f_{dex} = Fraction of year office worker is exposed = $(2000/8766) = 0.23$
- h = Height of reference room
- λ_h = Average air ventilation rate (room air changes per year)
- λ = Radon decay constant (yr^{-1})
- D_w = Radon diffusion coefficient through waste (m^2/yr)
- D_c = Radon diffusion coefficient through building foundation (m^2/yr)
- t_b = Thickness of building foundation (m)
- DF_R = Radon risk coefficient (health effects per pCi/ m^3 of radon)

2.2.4 Onsite individual

This exposure pathway describes the external gamma radiation dose to an individual who lives on an abandoned NORM waste storage or disposal site. The equation used to calculate the dose to this individual is:

$$D = \frac{C * M}{A} * e^{-\mu_c t_c} * \left(\frac{1 - e^{-\mu_w t_w}}{\mu_w t_w} \right) * f_{oex} * DFG \quad (D-4)$$

Equation D-4 is identical to equation D-1 except for the parameter f_{oex} which replaces the product $f_{wex} * f_{sh}$. The parameter f_{oex} is the equivalent exposure fraction for outside exposure. The value of $f_{oex} = 0.50$ takes into account both time spent outdoors directly on the contaminated ground (assumed to be one-fourth of the time) and time spent indoors where the exposure is reduced due to shielding by the structure.

2.2.5 Onsite Individual -- Indoor Radon Inhalation

This exposure pathway describes the health effects from indoor radon inhalation to an individual who lives in a house located on an abandoned NORM waste storage or disposal site. The equation used to calculate the health effects from radon inhalation is

$$R = \frac{C_R * \rho_w * E * f_{iex}}{h * \lambda_h} * \sqrt{\lambda * D_w} * e^{-(\sqrt{\lambda D_c} * t_b)} * DF_R \quad (D-5)$$

Equation D-5 is identical to equation D-3 except for the parameter f_{iex} . The parameter f_{iex} is the exposure fraction for indoor exposure and represents the fraction of time that the individual spends inside the house.

2.2.6 Member of CPG -- Direct Gamma Exposure

This exposure pathway describes the external gamma radiation dose received by an individual who resides near a NORM waste storage or disposal site. The individual is assumed to be located 100 m from the edge of the disposal pile. The equation used to calculate the radiation dose to this individual is:

$$D = \frac{C * M}{2 * A} * e^{-\mu_c t_c} * \left(\frac{1 - e^{-\mu_w t_w}}{\mu_w t_w} \right) * e^{-ax} * f_{oex} * DFG \quad (D-6)$$

where

D = Annual dose (mrem/yr)

C	=	Nuclide concentration in waste (pCi/g)
M	=	Mass of reference waste pile (g)
2	=	Factor to correct for exposure at edge of waste pile
A	=	Plane area of waste pile (m²)
μ_c	=	Attenuation coefficient of cover material (m⁻¹)
t_c	=	Thickness of cover material (m)
μ_w	=	Attenuation coefficient of waste material (m⁻¹)
t_w	=	Thickness of waste material (m)
a	=	Attenuation coefficient to correct for distance of member of CPG from edge of waste pile (m⁻¹)
x	=	Distance of member of CPG from edge of waste pile (100 m)
f_{oex}	=	Equivalent exposure fraction for outside exposure (dimensionless)
DFG	=	External gamma dose conversion factor (mrem/yr per pCi/m²)

As is the case for equation D-4, the factor f_{oex} in equation D-6 accounts for both the time spent outdoors and the time spent indoors where shielding reduces the dose rate from gamma radiation.

2.2.7 Member of CPG -- Inhalation of Contaminated Dust

The downwind transport of resuspended particulates (fugitive dusts) containing radionuclides can result in exposure to a member of the CPG via the inhalation of airborne particulates and the ingestion of foodstuffs contaminated by dust deposition. Exposure to direct radiation can also occur as a result of immersion of the individual in the radioactive dust cloud or from deposited radioactivity. However, the direct radiation dose from fugitive dusts is only a small fraction of either the inhalation or ingestion dose, and is not calculated. The inhalation dose from fugitive dusts is described in this subsection and is given by equation D-7. The ingestion dose is given by equation D-14 described in Subsection 2.2.12.

A Gaussian plume technique is used to model the transport of resuspended material and to trace the effects of airborne contaminants. The exposed individual is assumed to be located 100 m downwind from the edge of the NORM storage or disposal site. The equation used to calculate the dose to a member of the CPG from inhalation of contaminated dust is:

$$D = 2 q_d * \frac{f_w * f_{oex}}{a_i * V_a} * X_1^{-b-2} * U_i * DF_{inh} \quad (D-7)$$

where

- D = 50-year committed dose equivalent from one year's exposure (mrem)
- q_d = Atmospheric release rate (pCi/sec)
- f_w = Fraction of year wind blows in maximum direction (dimensionless)
- f_{oex} = Equivalent exposure fraction for outdoor exposure (dimensionless)
- a_i = Atmospheric stability constant (dimensionless)
- V_a = Average wind speed (m/sec)
- X_1 = Virtual distance to exposed individual (m)
= $100 + L/2 + 2.5W$, where L and W represent, respectively, the length and width of the disposal site
- U_i = Volume of air breathed in a year (m^3/yr)
- DF_{inh} = Inhalation dose conversion factor (mrem/pCi)
- b = $\sqrt{2/\pi} * V_d / (V_a * a_i)$
- V_d = Deposition velocity for particulates (m/sec).

The atmospheric release rate, q_d , for radionuclides in the waste is given by the equation

$$q_d = E_w * A * C$$

where

- E_w = Resuspension factor ($g/m^2 \cdot sec$)
- A = Area of waste site (m^2)
- C = Waste/soil nuclide concentration (pCi/g).

Using the methodology in NRC Regulatory Guide 3.59 (NRC87), a value for the resuspension factor can be obtained from the equation

$$E_w = \frac{3.156E+07}{0.5} f_r \sum R_s * F_s$$

where

- R_s = The resuspension rate at wind speed S
- F_s = The frequency of occurrence of wind speed S
- f_r = Respirable fraction of resuspended NORM.

The expression in Regulatory Guide 3.59 is modified by the respirable fraction f_r . Regulatory Guide 3.59 tabulates values of R_s and F_s for a typical tailings site. Using these tabulated values, the value of E_w is calculated to be $f_r * 1.35E-05$ g/m²-sec.

2.2.8 Member CPG -- Downwind Exposure to Radon

The risk to an exposed member of the CPG is calculated for downwind exposure to radon gas exhaled from waste piles containing radium-226. The exposed individual is assumed to be located 100 m downwind from the edge of the pile. Radon emanation rates from the waste piles are calculated based on average Ra-226 concentrations in the waste, radon exhalation rates, and exposed waste pile areas.

Several important factors govern the exhalation rate of radon including mineral form, material density and porosity, particle size distribution, and moisture content. Changing meteorological conditions such as atmospheric pressure, surface wind velocity, and differences between soil and air temperatures can also affect radon emanation rates. For this generic evaluation, average radon exhalation rates are employed that are believed to be representative of typical disposal sites where the waste would be disposed. These radon exhalation rates are also representative of sites where there is no cover material over the waste.

The equation for calculating the risk to a member of the CPG from downwind exposure to radon is:

$$R = 2q_R * \frac{f_w}{a_1 * V_a * X_1^2} * f_{oex} * DF_R \quad \text{--- (D-8) ---}$$

where

- R** = Risk from radon inhalation (health effects)
- q_R** = Atmospheric release rate for radon (pCi/sec)
- f_w** = Fraction of year wind blows in maximum direction (dimensionless)
- a₁** = Atmospheric stability constant (dimensionless)
- V_a** = Average wind speed (m/sec)
- X₁** = Virtual distance to exposed individual (m)
= 100 + L/2 + 2.5W, where L and W represent, respectively, the length and width of the disposal site
- f_{oex}** = Equivalent exposure fraction for outdoor exposure (dimensionless)
- DF_R** = Radon risk coefficient (health effects for one year's exposure to 1 pCi/m³ of radon).

The atmospheric release rate for radon is given by the expression

$$q_R = C_R * \rho_w * E * A * \sqrt{\lambda D_w}$$

where

- C_R** = Radium-226 concentration in the waste (pCi/g)
- ρ_w** = Waste density (g/m³)
- E** = Radon emanation coefficient (dimensionless)
- A** = Area of waste site (m²)
- λ** = Radon decay constant (sec⁻¹)
- D_w** = Radon diffusion coefficient through waste (m²/sec).

This expression is valid for radon diffusion at sites where the thickness of the waste is greater than about one meter. For agricultural sites where the waste is used as fertilizer, the above equation must be multiplied by $\tanh(\sqrt{\lambda D} * t)$, where t is the thickness of the till layer in meters (0.15 m).

2.2.9 Member of CPG -- Exposure to NORM in Building Materials

An estimate is made of exposures to individuals living in a house constructed of building materials that incorporate NORM wastes. Examples are wallboard containing phosphogypsum or coal ash. It is assumed that one part of NORM waste is mixed with two parts of non-contaminated material. Only direct exposure to gamma radiation is considered in this scenario.

The expression used to calculate the gamma dose to an individual from exposure to NORM in building materials is a modification of the equation used to calculate the dose to an individual from a large planar source (EPA87a). The large planar source equation is modified to take into account multiple exposures from finite sources (the walls and ceiling of the room). The building characteristics assumed in developing the equation are that the house contains seven or more rooms and that a fraction of the dose comes from rooms other than the one in which the person is standing. The average room size is taken to be 20 m², and the person is assumed to stand in the center of a room while being exposed.

The expression for the gamma dose to an exposed individual is:

$$D = C * \rho_w * f_{\text{tex}} * f_b * 2 * \frac{1}{2} * (1 + 2.55e^{-0.5\mu_1}) * \text{DFG} \quad (\text{D-9})$$

where

- D = Annual dose from gamma radiation (mrem/yr)
- C = Nuclide concentration in waste (pCi/g)
- ρ_w = Density of wallboard material (g/m³)
- f_{tex} = Exposure fraction for indoor exposure (dimensionless)
- f_b = Fraction of NORM in building materials (dimensionless)
- μ_1 = Gamma attenuation coefficient for building materials (cm²/g)
- DFG = External gamma dose conversion factor (mrem/yr per pCi/m²).

The factor of 2 in the equation takes account of the fact that each wall has two sides. The factor of one-half is a room size factor that takes account of the wall dimensions and the distance of a person from the walls. The factor of $2.55e^{-0.5\mu_1}$ accounts for contributions to the

total dose from radiation from walls in rooms other than the one in which the person is standing.

2.2.10 Member of CPG -- Ingestion of Drinking Water from a Contaminated Well

The ingestion dose is calculated for a member of the CPG assumed to be exposed by drinking water from a well that becomes contaminated as a result of groundwater transport of radionuclides from a NORM waste pile. The well is located 100 meters from the waste pile. The radionuclides move downward through the unsaturated zone to an aquifer beneath the waste site. In the aquifer, the waste components are transported by advection and dispersion to a location where the contaminated water is withdrawn from a well.

The equation used to calculate the ingestion dose to an individual who drinks water from a contaminated well is:

$$D = \frac{C * M * \lambda_L * f_o * U_d * DF_{ing}}{q_w} \quad (D-10)$$

where

- D = 50-year committed dose equivalent from one year's exposure (mrem)
- C = Nuclide concentration in waste (pCi/g)
- M = Mass of reference waste pile (g)
- λ_L = Fraction of each nuclide leached from inventory in a year (yr^{-1})
- f_o = Fraction of nuclide inventory arriving at the well from transport through the aquifer (dimensionless)
- U_d = Annual volume of water consumed by an individual (m^3/yr)
- q_w = Dilution volume for the well (m^3/yr)
- DF_{ing} = Ingestion dose conversion factor (mrem/pCi)

The expression used to calculate the fraction of each nuclide leached from inventory in a year, λ_L , is:

$$\lambda_L = \frac{I^2}{K_d * \rho_w * t_w * K_s} \quad (D-11)$$

where

- I = Annual water infiltration rate through the waste (m/yr)
- K_d = Equilibrium distribution coefficient of the waste/soil matrix (m³/kg)
(Assumed to be the same as the K_d for the aquifer.)
- ρ_w = Density of the waste/soil matrix (kg/m³)
- t_w = Thickness of the waste (m)
- K_s = Saturated hydraulic conductivity of the waste/soil matrix (m/yr).

The term I/K_s is the fraction of the year the waste is in contact with water. This correction for unsaturated leaching is contained in the EPA's PRESTO model (EPA87b).

The annual water infiltration rate is taken to be one-half the annual rainfall. The density of the waste/soil matrix is assumed to be the same as the density of the aquifer.

The expression used to calculate f_o, the fraction of the nuclide inventory arriving at the well from transport through the aquifer is:

$$f_o = \frac{V_w}{L * R * \lambda_L} (1 - e^{-\lambda_L RL/V_w}) \quad (D-12)$$

where

- V_w = Horizontal velocity of aquifer (m/yr)
- L = Length of waste site parallel to aquifer flow (m)
- R = Retardation factor = 1 + (ρ_a/p) * K_d
- ρ_a = Aquifer density (kg/m³)
- p = Aquifer porosity (dimensionless)
- K_d = Equilibrium distribution coefficient in the aquifer (m³/kg).

The dilution volume for the well, q_w, is assumed to be the annual rainfall multiplied by the area of the waste pile.

2.2.11 Member of CPG -- Ingestion of Foodstuffs Contaminated by Well Water

The ingestion dose is also calculated for a member of the CPG assumed to be exposed by eating foodstuffs irrigated with well water that becomes contaminated as a result of groundwater transport of radionuclides from a NORM waste pile. The equation used to calculate this ingestion dose is:

$$D = \frac{C * M * \lambda_L * f_{cv} * U_c * DF_{ing}}{c_v} \quad (D-13)$$

Equation D-13 is identical to equation D-10 except for the factor U_c which replaces the factor U_d . The factor U_c (m^3/yr) is the annual equivalent foodstuff consumption uptake factor for an individual. It is given by

$$U_c = U_w - U_d$$

where U_w is the annual equivalent water uptake factor for an individual.

2.2.12 Member of CPG -- Ingestion of Foodstuffs Contaminated by Dust Deposition

This exposure pathway describes the ingestion dose to an individual who eats foodstuffs contaminated by fallout from fugitive dusts. As described in Subsection 2.2.7, the downwind transport of resuspended particulates contaminated with radionuclides can cause exposure to a member of the CPG through the inhalation of the dust particles or the ingestion of crops grown in soils contaminated with radioactive fallout. The inhalation dose is calculated by equation D-7. The ingestion dose is calculated by:

$$D = 2q_d * \frac{f_w}{a_i * V_a} * X_1^{-b-2} * \frac{V_d * t_{dep}}{2} * \frac{U_f}{X_{root}} * DF_{ing} \quad (D-14)$$

where

D = 50 year committed dose equivalent for one year's exposure (mrem)

q_d = Atmospheric release rate (pCi/sec)

f_w = Fraction of year wind blows in maximum direction (dimensionless)

a_i	=	Atmospheric stability constant (dimensionless)
V_a	=	Average wind speed (m/sec)
X_1	=	Virtual distance to exposed individual (m) = $100 + L/2 + 2.5W$, where L and W represent, respectively, the length and width of the disposal site
V_d	=	Deposition velocity for particulates (m/sec).
t_{dep}	=	Deposition time (sec)
U_f	=	Food uptake factor (kg/yr)
X_{root}	=	Root uptake factor (kg/m ²)
DF_{ing}	=	Ingestion dose conversion factor (mrem/pCi)
b	=	$\sqrt{2/\pi} * V_d / (V_a * a_i)$

The atmospheric release rate, q_d , is calculated as explained in Subsection 2.2.7. The root uptake factor, X_{root} , is the product of the average root depth and the soil density.

2.2.13 Member of CPG -- Ingestion of Foodstuffs Grown on Repeatedly Fertilized Soil

This exposure pathway describes the ingestion dose to an individual who eats foodstuffs grown in soil that is repeatedly fertilized with phosphate fertilizer or water treatment sludge. Fertilizers are spread over agricultural fields and diluted by mixing with the soil. Hence the incremental radionuclide concentrations in the soil are much lower than the radionuclide concentrations in the fertilizer itself. Over time, as fertilizers continue to be applied, the radionuclide concentrations in the soil are expected to increase until equilibrium is reached with competing mechanisms that remove fertilizers, and their radioactive constituents, from the soils. These removal mechanisms include plant uptake, leaching by infiltration of surface water, and wind and water erosion. The number of years required for radionuclide concentrations in repeatedly fertilized soils to reach equilibrium is not known and can only be estimated with considerable uncertainty. For this ingestion dose calculation, a time period of 20 years of repeated fertilizer application is assumed.

Radionuclide concentrations are assumed to continue to increase during this period, and no credit is taken for depletion mechanisms that might remove radionuclides from the soil.

The equation used to calculate the ingestion dose to a person who eats foodstuffs grown in repeatedly fertilized soil is:

$$D = 10^3 * C * U_f * DF_{ing} \quad (D-15)$$

where

- D = 50-year committed dose equivalent from one year's exposure (mrem)
- C = Nuclide concentration in waste (pCi/g)
- 10^3 = Conversion factor to convert from pCi/g to pCi/kg
- U_f = Food uptake factor (kg/yr)
- DF_{ing} = Ingestion dose conversion factor (mrem/pCi)

2.2.14 General Population -- Downwind Exposure to Resuspended Particulates

This exposure pathway describes the dose to the general population in the vicinity of the disposal site from the downwind transport of resuspended particulates (fugitive dusts) containing radionuclides. Doses to the exposed population can result from the inhalation of airborne particulates, ingestion of crops and produce contaminated with deposited fugitive dusts, and direct radiation from deposited radioactivity. The exposed population is assumed to reside within a radius of 8×10^4 meters (50 miles) of the NORM waste storage or disposal site.

The equation used to calculate the population dose from this exposure pathway is:

$$CD = \sqrt{\frac{2}{\pi}} * \frac{q_d}{a_i * V_a * b} * \left(\frac{1}{X_1^b} - \frac{1}{X_2^b} \right) * PD * \quad (D-16)$$

$$\left[(U_i * DF_{inh}) + (V_d * \frac{t_{dep}}{2} * DFG) + \left(\frac{V_d * t_{dep}}{2} * \frac{U_f}{X_{root}} * DF_{ing} \right) \right]$$

where

CD	=	Population dose (person-mrem)
PD	=	Population density (persons/m ²)
q _d	=	Atmospheric release rate (pCi/sec)
a _i	=	Atmospheric stability constant (dimensionless)
V _a	=	Average wind speed (m/sec)
X ₁	=	Minimum distance to exposed individual (m) = 100 + L/2 + 2.5W
X ₂	=	Maximum distance of integral used to evaluate exposed population (m)
U _i	=	Annual breathing rate (m ³ /yr)
V _d	=	Deposition velocity for particulates (m/sec).
t _{dep}	=	Deposition time (sec)
U _f	=	Food uptake factor (kg/yr)
X _{root}	=	Root uptake factor (kg/m ²)
DF _{inh}	=	Inhalation dose conversion factor (mrem/pCi)
DF _{ing}	=	Ingestion dose conversion factor (mrem/pCi)
DFG	=	External gamma dose conversion factor (mrem/yr per pCi/m ²).
b	=	$\sqrt{2/\pi} * V_d / (V_a * a_i)$

The atmospheric release rate, q_d, for radionuclides is calculated the same way for the population dose from downwind exposure as for the individual dose from downwind exposure (see Subsection 2.2.7).

2.2.15 General Population -- Downwind Exposure to Radon

The risk to a representative population in the vicinity of the disposal site is calculated for downwind exposure to radon gas exhaled from NORM waste piles containing radium-226. As is the case for the calculation of the radon risk to an individual member of the CPG (Subsection 2.2.8), radon emanation rates from the waste piles are calculated based on

average Ra-226 concentrations in the waste, representative radon exhalation rates, and exposed pile areas for representative waste piles. The exposed population is assumed to reside within a 8×10^4 m (50 mi) radius of the waste pile.

The equation used to calculate the population risk from downwind exposure to radon gas is:

$$PR = \sqrt{\frac{L}{r}} * \frac{q_R}{V_a * a_i} * \ln\left(\frac{X_2}{X_1}\right) * PD * DF_R \quad (D-17)$$

where

- PR = Population risk from radon inhalation (health effects)
- q_R = Atmospheric release rate for radon (pCi/sec)
- V_a = Average wind speed (m/sec)
- a_i = Atmospheric stability constant (dimensionless)
- X_2 = Maximum distance of integral used to evaluate exposed population (m)
- X_1 = Minimum distance to exposed individual (m)
= $100 + L/2 + 2.5 V$
- PD = Population density (persons/m²)
- DF_R = Radon risk coefficient (health effects per pCi/m³ of radon).

The atmospheric release rate for radon, q_R , is calculated as shown in Subsection 2.2.8 which describes the dose to an individual from downwind exposure to radon gas.

2.2.16 General Population -- Ingestion of River Water Contaminated via the Groundwater Pathway

This exposure pathway describes the population dose from the use of river water that has become contaminated by the groundwater migration of radionuclides from the NORM waste storage or disposal site. The equation used to calculate the population dose for this exposure scenario is:

$$CD = \frac{C * M * \lambda_L * f_o * U_w * EP * DF_{ing}}{q_r} \quad (D-18)$$

where

- CD = 50-year committed dose to the population from one year of exposure (person-mrem)
- C = Nuclide concentration in waste (pCi/g)
- M = Mass of reference waste pile (g)
- λ_L = Fraction of each radionuclide leached from inventory in a year (yr^{-1})
- f_o = Fraction of nuclide inventory arriving at the river from transport through the aquifer (dimensionless)
- U_w = Annual water equivalent uptake factor for an individual (m^3/yr)
- EP = Exposed population (persons)
- q_r = Flow rate of the river (m^3/yr)
- DF_{ing} = Ingestion dose conversion factor (mrem/pCi)

The factors λ_L and f_o are calculated as described in Subsection 2.2.10.

The exposed population is estimated by multiplying the population density by an assumed area in which people live who would use the river water for drinking or would consume foodstuffs contaminated by agricultural use of the water. This "use area" is assumed to be approximately 1,000 mi^2 .

2.2.17 General Population -- Ingestion of River Water Contaminated by Surface Runoff

This exposure pathway describes the population dose from the use of river water contaminated through surface runoff of rainwater that transports radionuclides leached from a NORM waste pile. The equation used to calculate the population dose for this exposure scenario is:

$$CD = C * \rho_w * \frac{f_{dt} * I * r_f * A}{R * q_r} * U_w EP * DF_{ing} \quad (D-19)$$

where

- CD = 50-year committed dose to the population from one year of exposure (person-mrem)
- C = Nuclide concentration in waste (pCi/g)
- ρ_w = Waste density (g/m³)
- f_{dt} = Dilution factor for surface water transport of waste (dimensionless)
- I = Annual water infiltration rate through the waste (m/yr)
- r_f = Runoff fraction (dimensionless)
- A = Area of waste site (m²)
- R = Retardation factor (dimensionless)
- q_r = Flow rate of the river (m³/yr)
- U_w = Annual water equivalent uptake factor for an individual (m³/yr)
- EP = Exposed population (persons)
- DF_{ing} = Ingestion dose conversion factor (mrem/pCi)

The annual water infiltration rate through the waste, I, is assumed to be one-half the annual rainfall at the site. The retardation factor, R, for surface runoff is assumed to be the same as it is for the aquifer (i.e., groundwater) transport of radionuclides. In the aquifer this retardation factor is given by:

$$R = 1 + (\rho_a / p) * K_d \quad (D-20)$$

where

- ρ_a = Aquifer density (kg/m³)
- p = Aquifer porosity (dimensionless)
- K_d = Equilibrium distribution coefficient (m³/kg).

2.2.18 General Population -- Ingestion of Foodstuffs Grown on Repeatedly Fertilized Soil

This exposure pathway describes the ingestion dose to an exposed population from eating foodstuffs grown in repeatedly fertilized soil. This scenario is similar to that described in Subsection 2.2.13 for the ingestion dose to an individual who eats food grown in soil that is repeatedly fertilized for a period of 20 years. The equation for calculating the ingestion dose to the exposed population is

$$CD = 10^3 * C * U_f * DF_{ing} * POP \quad (D-21)$$

where

CD = 50-year committed dose to the exposed population from one year of exposure (person-mrem)

POP = The population eating food grown on repeatedly fertilized soil (persons).

The other parameters in D-21 have the same meaning as in equation D-15.

The exposed population is obtained by estimating how many persons would obtain their annual average vegetable requirement from agricultural fields fertilized by phosphate fertilizer. The equation used to calculate the exposed population is

$$(POP) = \frac{A}{I_c}$$

where

A = Plane area of fertilized field (m²)

I_c = Areal requirement for an individual for vegetables consumed annually (m²/person)

The individual areal requirement, I_c, is 292 m²/person as determined from the equation:

$$I_c = \frac{\text{Individual Consumption Rate}(190 \text{ kg/yr})}{\text{Vegetable Production Density}(0.65 \text{ kg/m}^2\text{-yr})}$$

Values for the individual consumption rate and the vegetable production density are taken from the EPA's Background Information Document (EPA88a).

2.3 INPUT PARAMETERS

Values of the various input parameters used with the equations of Section 2.2 to evaluate individual and population doses from the storage and disposal of diffuse NORM wastes are presented in this section. Input parameters include generic parameters that are assumed to be the same for all NORM sectors, parameters that are site and NORM-sector specific, and parameters that are nuclide specific.

Values of generic parameters that are assumed to have the same value regardless of waste type or site location are shown in Table D.2-1.

Values of site-specific parameters are shown in Tables D.2-2 and D.2-3. Site specific parameters include reference site dimensions and radionuclide concentrations which are shown in Table D.2-2, and equilibrium distribution coefficients (K_d) and other site-specific parameters shown in Table D.2-3. The rationale for the values used for these site-specific parameters is presented in Chapter B, in part, and in this chapter.

All of the dose and health risk calculations for fertilized agricultural sites are based on radionuclide concentrations resulting from repeated applications of fertilizer during a 20-year period. As previously described in Section 2.2.13, fertilizers are spread over agricultural fields and diluted by mixing with the soil. For repeated applications, the radionuclide concentrations in the soil increase until an equilibrium is reached between the rate at which fertilizer is added to the soil and the rate at which it is removed by plant uptake, leaching, wind and water erosion, and other removal mechanisms. The number of years required for radionuclide concentrations to reach equilibrium in repeatedly fertilized soils is difficult to estimate with any degree of certainty, and may be nuclide dependent.

All of the individual and population exposure scenarios involving the application of fertilizer to agricultural fields are based on radionuclide concentrations in the soil resulting from 20 years of fertilizer application. The radionuclide concentrations are assumed to increase linearly during this period, and no credit is taken for depletion mechanisms that could remove radionuclides. For phosphate fertilizers, the application rate is assumed to be 37 kg per hectare, applied annually (see Section 3.4.1). For water treatment sludge used as

Table D.2-1. Generic input parameters for diffuse NORM risk assessment.

Symbol	Parameter	Units	Value
A_f	Total amount of fertilizer applied per year	g/yr	4.8E+12
a	Attenuation coefficient for distance of average CPG from waste pile	m^{-1}	5.0E-3
a_i	Atmospheric stability constant (50% C stability; 50% D stability)	--	7.0E-2
D_c	Radon diffusion coefficient through concrete	m^2/yr	1.6E+1
D_w	Radon diffusion coefficient through waste	m^2/yr	
	- humid site		2.2E+1
	- dry site		6.3E+1
d_d	Dust loading in air breathed	g/m^3	5.0E-4
d_{rt}	Root depth in fertilized soil	m	1.0E+0
EP	Exposed population using river	persons	3.3E+3
F_f	Annual rate of fertilizer application	$g/m^2\text{-yr}$	3.7E+0
f_b	Fraction of NORM in building materials	--	3.3E-1
f_w	Fraction of year wind blows in maximum direction	--	9.3E-2
f_{ds}	Soil dilution factor (fertilizer)	--	2.3E-3
f_{dt}	Dilution factor for surface water transport of waste	--	7.0E-1
f_{sh}	Shielding factor for worker exposure	--	6.0E-1
f_{dex}	Fraction of year office worker is exposed	--	2.3E-1
f_{iex}	Exposure fraction for indoor exposure	--	7.5E-1
f_{oex}	Equivalent exposure fraction for outside exposure	--	5.0E-1
f_{wex}	Fraction of year waste pile worker is exposed	--	1.8E-1
h	Height of reference room	m	2.3E+0
I_c	Areal requirement for vegetables consumed by an individual	m^2	2.9E+2
p	Aquifer porosity	--	3.3E-1
q_r	Flow rate of river	m^3/yr	1.0E+8
r_f	Surface water runoff fraction	--	5.0E-1
T	Years of fertilizer application for repeatedly fertilized soils	yr	2.0E+1
t_b	Thickness of building floor (cement)	m	1.5E-1

Table D.2-1. Continued.

Symbol	Parameter	Units	Value
t_{dep}	Deposition time for particulates	sec	6.3E+8
U_d	Volume of drinking water consumed annually by an individual	m ³ /yr	3.7E-1
U_i	Volume of air breathed in a year	m ³ /yr	8.0E+3
V_a	Average wind speed	m/sec	4.5E+0
V_d	Deposition velocity for particulates	m/sec	1.0E-3
V_w	Horizontal velocity of aquifer	m/yr	2.0E+1
X_{root}	Root uptake factor	kg/m ²	7.0E+2
X_2	Maximum distance of integral used to evaluate exposed population	m	8.0E+4
x	Distance of well and of average CPG from edge of waste pile	m	1.0E+2
λ	Radon decay constant	yr ⁻¹	6.6E+1
λ_h	Room air changes per year	yr ⁻¹	1.8E+4
μ_c	Gamma linear attenuation coefficient for cover material	m ⁻¹	1.5E+1
μ_i	Gamma mass attenuation coefficient for building material (wallboard)	cm ² /g	1.0E-1
μ_w	Gamma linear attenuation coefficient for waste material	m ⁻¹	1.5E+1
ρ_a	Aquifer density	g/cm ³	1.8E+0

Table D.2-2. Reference disposal pile parameters and radionuclide concentrations for diffuse NORM risk assessment.

Parameter	Units	Uranium Overburden	Phosphate Waste	Phosphate Fertilizer	Coal Ash	Water Treatment Sludge -- Fertilizer	Water Treatment Sludge -- Landfill	Mineral Processing Waste	Oil & Gas Scale/Sludge	Geothermal Energy Waste
Location of Reference Pile		Texas	Florida	Illinois	Northeast	Illinois	Illinois	Arizona	Texas	California
Waste Mass Reference Pile	MT	5.6E+07	5.0E+07	3.4E+05	1.5E+06	3.4E+05	5.1E+05	3.0E+07	1.3E+06	7.4E+05
Reference Disposal Pile										
Length	m	1200	1750	1200	500	1200	400	700	400	320
Width	m	1200	1750	1200	500	1200	400	700	400	320
Thickness	m	20	7	0.15	5.0	0.15	2	30	4.5	4
Cover	m	None	None	None	None	None	0.30	None	None	0.15
Surface Area	m ²	1.4E+06	3.0E+06	1.4E+06	2.5E+05	1.4E+06	1.6E+05	4.9E+05	1.6E+05	1.0E+05
No. of Reference Piles in U.S.		1.4E+01	1.5E+01	9.4E+05	1.3E+03	4.4E+02 ^a	2.3E+02 ^b	6.7E+02	1.0E+01	2.0E+00
Average Waste Density	g/cm ³	2.0	2.35	1.6	1.2	1.6	1.6	2.0	1.8	1.8
Nuclide Concentration										
Po-210	pCi/g	16.6	26.4	5.7	7.0	10.0	10.0	25.0	155.0	110.0
Pb-210	pCi/g	16.6	26.4	5.7	6.8	10.0	10.0	25.0	155.0	110.0
Ra-226	pCi/g	23.7	33.0	8.2	3.7	16.0	16.0	35.0	155.0	160.0
Th-228	pCi/g	1.0	0.27	1.1	3.2	0.2	0.2	10.0	55.0	30.0
Ra-228	pCi/g	1.0	0.27	1.1	1.8	20.0	20.0	10.0	55.0	110.0
Th-230	pCi/g	23.7	13.0	53.0	2.3	0.2	0.2	35.0	--	--
Th-232	pCi/g	1.0	0.27	1.0	2.1	0.2	0.2	10.0	--	--
U-234	pCi/g	23.7	6.2	55.3	3.3	4.0	4.0	35.0	--	--
U-238	pCi/g	23.7	6.0	55.3	3.3	4.0	4.0	35.0	--	--
U-235	pCi/g	1.2	0.3	2.8	0.16	0.03	0.03	1.8	--	--

^a Assumes that all of the water treatment sludge generated during the 20-year reference period is used as fertilizer.

^b Assumes that all of the water treatment sludge generated during the 20-year reference period is disposed of at landfills.

Table D.2-3. Site-specific input parameters for diffuse NORM risk assessment.

Parameter	Symbol	Units	Uranium Overburden	Phosphate Waste	Phosphate Fertilizer	Coal Ash	Water Treatment Sludge -- Fertilizer	Water Treatment Sludge -- Landfill	Mineral Processing Waste	Oil & Gas Scale/Sludge	Geothermal Energy Waste
Distribution Coefficients											
Po-210	K_d	m ³ /kg	0.050	0.50	0.50	0.10	0.50	0.50	0.050	0.10	0.050
Pb-210	K_d	m ³ /kg	0.090	0.90	0.90	0.10	0.90	0.90	0.090	0.10	0.090
Ra-226	K_d	m ³ /kg	0.045	0.45	0.45	0.075	0.45	0.45	0.045	2.5	0.045
Th-228	K_d	m ³ /kg	15.0	150.0	150.0	3.0	150.0	150.0	15.0	2.5	15.0
Ra-228	K_d	m ³ /kg	0.045	0.45	0.45	0.075	0.45	0.45	0.045	2.5	0.045
Th-230	K_d	m ³ /kg	15.0	150.0	150.0	3.0	150.0	150.0	15.0	---	---
Th-232	K_d	m ³ /kg	15.0	150.0	150.0	3.0	150.0	150.0	15.0	---	---
U-234	K_d	m ³ /kg	0.045	0.45	0.45	0.050	0.45	0.45	0.045	---	---
U-238	K_d	m ³ /kg	0.045	0.45	0.45	0.050	0.45	0.45	0.045	---	---
U-235	K_d	m ³ /kg	0.045	0.45	0.45	0.050	0.45	0.45	0.045	---	---
Waste Porosity		---	0.40	0.25	0.25	0.3	0.35	0.35	0.40	0.40	0.40
Respirable Fraction	f_r	---	0.50	0.20	0.50	0.1	0.7	0.7	0.50	0.05	0.05
Radon Emanation Coefficient	E	---	0.30	0.20	0.30	0.04	0.40	0.40	0.30	0.10	0.25
Annual Rainfall at Site		cm/yr	72.5	124.5	90.7	110.0	90.7	90.7	28.3	51.0	25.0
Saturated Hydraulic Conductivity	K_s	m/yr	3.15E+04	3.15E+02	3.15E+04	1.00E+02	3.15E+04	3.15E+04	3.15E+04	3.0E+02	3.0E+03
Water Percolation Rate Through Waste	I	m/yr	0.36	0.62	0.45	0.55	0.45	0.45	0.14	0.26	0.12
Dilution Volume for Well	q_w	m ³ /yr	1.0E+06	3.7E+06	1.3E+06	2.8E+05	1.1E+06	1.5E+05	1.4E+05	8.2E+04	2.5E+04
Population Density for Atmospheric Pathways per Site	PD	persons per mi ²	64	216	210	780	210	210	46	64	181
Population Using River Water per Site	EP	persons	70,000	235,000	230,000	850,000	230,000	230,000	50,000	70,000	200,000
Virtual Distance to Exposed Individual	X_1	m	3700	5350	3700	1600	3700	1300	2200	1300	1060

D-2-25

fertilizer, the application rate is assumed to be 10,000 kg per hectare (4.5 tons per acre), applied every other year (see Section 6.5.1). The fertilizer is assumed to be mixed with the top 0.15 m of soil. The radionuclide concentrations for phosphate fertilizer and water treatment sludge shown in Table D.2-2 are adjusted for fertilizer application rates and soil mixing ratios to obtain the radionuclide concentrations in repeatedly fertilized soil used in the risk calculations.

The water percolation rate through the waste, I , shown in Table D.2-3 is assumed to be equal to one-half the annual average rainfall at the waste site. The dilution volume for the well, q_w , is assumed to equal the rainfall rate multiplied by the pile area.

Population densities used in evaluating total population health effects for downwind exposure to resuspended particulates are the average population densities for the state listed under each NORM waste sector in Table D.2-3. Exposed populations used in evaluating total population health effects from ingestion of contaminated river water are also based on the average population densities in Table D.2-3, and are estimated as described in Subsection 2.2.16.

Nuclide-specific parameters used in this analysis include equilibrium distribution coefficients (K_d), leach rates, dose conversion factors, and equivalent food and water uptake factors. Values for equilibrium distribution coefficients are site specific and are shown in Table D.2-3. Values for leach rates are calculated using Equation D-11 of Section 2.2.10. Equation D-11 is derived from the leaching model used by the U.S. Environmental Protection Agency in the PRESTO-EPA-POP environmental transport risk assessment code (EPA87b).

The dose and risk conversion factors used in this analysis are shown in Table D.2-4. Dose conversion factors for ingestion and inhalation are from the EPA's Federal Guidance Report No. 11, which provides guidance for the control of occupational exposures to radiation (EPA88b). Inhalation and ingestion dose conversion factors represent 50-year committed dose equivalents from one year of intake. Dose conversion factors for direct exposure to gamma radiation are from guidance for modifying PRESTO-EPA-CPG to reflect major recent changes in the EPA's dose calculation methodology. They represent effective whole body dose equivalents from external exposure during one year.

Table D.2-4. Dose and risk conversion factors.**I. Dose Conversion Factors**

Nuclide	Inhalation (mrem/pCi)^a	Ingestion DF (mrem/pCi)^a	Direct Gamma (mrem/yr per pCi/m²)
Po-210	9.4E-03	1.9E-03	8.55E-10
Pb-210	1.4E-02	5.4E-03	2.91E-07
Ra-226	8.6E-03	1.3E-03	1.67E-04
Th-228	3.4E-01	4.0E-04	3.37E-04
Ra-228	4.8E-03	1.4E-03	9.04E-05
Th-230	3.3E-01	5.5E-04	8.88E-08
Th-232	1.6E+00	2.7E-03	6.56E-08
U-234	1.3E-01	2.8E-04	8.00E-08
U-238	1.2E-01	2.5E-04	6.41E-08
U-235	1.2E-01	2.7E-04	1.67E-05

a 50-year committed dose equivalent from one year of intake (uptake).

II. Risk Conversion Factors.^b

Nuclide	Inhalation (Risk per pCi inhaled)	Ingestion DF (Risk per pCi ingested)	Direct Gamma (Risk per pCi/m²)
Po-210	1.5E-09	2.9E-10	3.3E-16
Pb-210	2.2E-09	8.4E-10	1.1E-13
Ra-226	1.3E-09	2.0E-10	6.5E-11
Th-228	5.3E-08	6.2E-11	1.3E-10
Ra-228	7.4E-10	2.2E-10	3.5E-11
Th-230	5.1E-08	8.5E-11	3.5E-14
Th-232	2.5E-07	4.2E-10	2.6E-14
U-234	2.0E-08	4.3E-11	3.1E-14
U-238	1.9E-08	3.9E-11	2.5E-14
U-235	1.9E-08	4.2E-11	6.5E-12

b 70-year lifetime risk of a fatal cancer from one year of exposure.

Table D.2-4. Continued.

II. Radon Risk Conversion Factors.^c

<u>Rn-222 and Daughters</u>	<u>Inhalation Risk per pCi/m³</u>
Indoor Exposure	4.9E-06
Outdoor Exposure	4.9E-07

^c 10-year lifetime risk of fatal cancer of one year of exposure to Rn-222 and Rn-222 daughters.

Risk conversion factors in Table D.2-4 are based on the radiation risk factors in Table 6-27 of Volume I of the EPA's "Environmental Impact Statement for NESHAPS Radionuclides" (EPA89a). They represent lifetime (i.e., 70 year) risks of fatal cancers from one year of exposure. A quality factor of 1 has been used to convert from rads to rems for low-LET (i.e., gamma) radiation, and a quality factor of 20 has been used to convert from rads to rems for high-LET (i.e., alpha) radiation.

Equivalent uptake factors for food and water are shown in Table D.2-5. These factors are calculated by the PATHRAE-EPA performance assessment code (EPA87a) using PRESTO dose assessment methodology. The equivalent uptake factors quantify, on a nuclide-specific basis, the annual amount of nuclide uptake by an individual from all potential ingestion sources. For ingestion pathways involving the use of contaminated water, the water equivalent uptake factor is the total equivalent drinking water consumption (m^3/yr) that would give the same annual nuclide uptake as would occur from the consumption of contaminated vegetation, meat, milk, seafood, and actual water consumption. For pathways involving food grown in contaminated soil, the food equivalent uptake factor is the equivalent amount of soil material (kg/yr) an individual would have to directly consume in order to ingest the same amount of a particular nuclide that is ingested by eating contaminated foods. Since water-to-soil and soil-to-plant transfer factors, and other related factors may be nuclide dependent, the equivalent water and food uptake factors are nuclide dependent.

Table D.2-5. Equivalent uptake factors.^a

Nuclide	Food Uptake Factor U_F (kg/yr)	Water Uptake Factor U_W (m³/yr)
Po-210	1.31E-02	9.43E-01
Pb-210	1.31E-02	9.43E-01
Ra-226	1.31E-02	9.43E-01
Th-228	1.29E-02	9.39E-01
Ra-228	1.29E-02	9.39E-01
Th-230	1.31E-02	9.43E-01
Th-232	1.29E-02	9.39E-01
U-234	2.21E-02	8.76E-01
U-238	2.21E-02	8.76E-01
U-235	2.21E-02	8.76E-01

a See text for details.

D.3 RISK ASSESSMENT RESULTS

The risk assessment equations of Section 2.2 were used with the input data of Section 2.3 to evaluate doses and health effects to individuals and populations from the storage or disposal of diffuse NORM wastes. The results of these risk calculations are presented in this section.

3.1 WORKER DOSES AND RISKS

Table D.3-1 gives the doses and risks to workers at the storage or disposal sites from the direct gamma exposure and dust inhalation pathways. As explained in subsection 2.2.1, the worker is assumed to spend 80 percent of each working day on the disposal pile and to use machinery such as a grader or bulldozer. Direct gamma exposures are estimated to result in the highest worker doses and risks -- typically about three orders of magnitude larger than the doses and risks from dust inhalation. The direct gamma exposure doses are estimated to range from $6.5\text{E}+2$ mrem/yr for direct exposure to oil and gas scale/sludge to 0.006 mrem/yr for direct exposure to radiation from a field repeatedly fertilized with phosphate fertilizer. Estimated 70-year lifetime risks of fatal cancer from one year of exposure range from $2.5\text{E}-04$ for exposure from oil and gas scale/sludge to $2.4\text{E}-09$ for exposure from a repeatedly fertilized field.

Estimated health effects from radon inhalation to office workers who work inside buildings at the NORM storage and disposal sites are given in Table D.3-2. Estimated 70-year lifetime risks of fatal cancer from one year of exposure for these office workers range from $9.3\text{E}-02$ at the geothermal waste site to $1.2\text{E}-04$ at the landfill site for water treatment sludge. Health effects to office workers from indoor radon inhalation dominate the worker risks at the NORM waste sites. In general, the cancer risks from radon inhalation to persons working in offices located on top of waste piles are estimated to be about three orders of magnitude larger than the cancer risks from gamma exposure to persons working on the NORM waste piles.

Table D.3-1. Worker doses and health effects from storage or disposal of diffuse NORM.

<u>Exposure Scenario</u>	<u>Uranium Overburden</u>	<u>Phosphate Waste</u>	<u>Phosphate Fertilizer</u>	<u>Coal Ash</u>	<u>Water Treatment Sludge -- Fertilizer</u>	<u>Water Treatment Sludge -- Landfill</u>	<u>Mineral Processing Waste</u>	<u>Oil & Gas Scale/Sludge</u>	<u>Geothermal Waste</u>
Direct Gamma Exposure									
Dose (mrem/yr) ^a	6.5E+01	9.9E+01	6.2E-03	1.6E+01	2.3E+00	8.0E-01	1.5E+02	6.5E+02	6.7E+01
Health Effects ^c	2.5E-05	3.8E-05	2.4E-09	6.3E-06	8.8E-07	3.1E-07	5.9E-05	2.5E-04	2.6E-05
Dust Inhalation									
Dose (mrem) ^b	2.8E-02	1.2E-02	1.7E-05	1.1E-02	1.3E-04	4.8E-05	6.9E-02	4.0E-02	2.5E-02
Health Effects ^c	4.3E-09	1.9E-09	2.7E-12	1.6E-09	2.0E-11	7.6E-12	1.1E-08	6.3E-09	3.8E-09

^a The annual whole body effective dose equivalent (mrem/yr).

^b The 50-year committed dose equivalent (mrem) from one year of intake.

^c The 70-year lifetime risk of a fatal cancer from one year of exposure.

Table D.3-2. Risks from radon inhalation.

<u>Exposure Scenario</u>	<u>Uranium Overburden</u>	<u>Phosphate Waste</u>	<u>Phosphate Fertilizer</u>	<u>Coal Ash</u>	<u>Water Treatment Sludge -- Fertilizer</u>	<u>Water Treatment Sludge -- Landfill</u>	<u>Mineral Processing Waste</u>	<u>Oil & Gas Scale/Sludge</u>	<u>Geothermal Waste</u>
Office Worker Health Effects^a	1.8E-02	1.2E-02	---	1.4E-04	---	1.2E-04	2.7E-02	2.1E-02	9.3E-02
Onsite Individual Health Effects^a	6.0E-02	3.9E-02	3.0E-06	4.5E-04	1.0E-03	3.8E-04	8.9E-02	7.0E-02	3.1E-01
Member of CPG Health Effects^a	4.3E-07	2.8E-07	5.4E-12	3.0E-09	1.6E-09	2.5E-09	6.3E-07	4.6E-07	1.9E-06
Population Health Effects^a	3.8E-03	1.6E-02	1.6E-07	7.8E-05	4.7E-05	1.2e-05	1.7e-03	6.8e-04	5.5E-03

-
- a** The 70-year lifetime risk of a fatal cancer from one year of exposure. Health effects to the office worker and the onsite individual are for indoor exposure. Health effects to the member of the CPG located 100 m downwind of the site are for outdoor exposure.
- b** The number of excess fatal cancers expected in the exposed population as a result of one year of exposure. The number of persons in the exposed population is given in Table D.2-3.

3.2 DOSES AND RISKS TO MEMBERS OF THE CRITICAL POPULATION GROUP (CPG)

Estimated doses and risks to members of the CPG are shown in Table D.3-2 for radon inhalation scenarios and in Table D.3-3 for all other exposure scenarios that were evaluated. The CPG is assumed to be located 100 meters away from the waste site. The cancer risks from indoor radon inhalation dominate the CPG risk calculations. Estimated 70-year lifetime risks of fatal cancer from one year of exposure to persons living in houses located on abandoned NORM waste storage or disposal sites range from $3.1\text{E}-01$ at the geothermal waste site to $3.0\text{E}-06$ on a repeatedly fertilized field (see Table D.3-2).

For exposure scenarios other than radon inhalation (Table D.3-3), the direct gamma exposure pathways dominate. The highest exposures, of the order of $1.0\text{E}+04$ mrem/yr, and highest risks, of the order of $5.0\text{E}-03$ lifetime risk of fatal cancer from one year of exposure, result from the use of phosphate and mineral processing wastes in wallboard for home construction. Direct gamma exposures to persons who reside at abandoned waste sites are estimated to range from about $3.0\text{E}+03$ mrem/yr at the oil and gas scale/sludge site to about 0.03 mrem/yr on a repeatedly fertilized field. Estimated 70-year lifetime risks of fatal cancer from one year of exposure range from $1.2\text{E}-04$ at the oil and gas scale/sludge site to $1.1\text{E}-08$ at the repeatedly fertilized field. Doses and health effects from consumption of contaminated foodstuffs are estimated to be very small compared to doses and health effects from direct gamma exposure.

3.3 POPULATION DOSES AND RISKS

Estimated population risks from downwind exposure to radon are given in Table D.3-2. The collective doses and risks from other exposure pathways that were evaluated are given in Table D.3-4.

The largest collective doses and risks are calculated for the exposure pathway involving the use of river water contaminated by surface runoff. For this exposure pathway the estimated collective doses range from $1.1\text{E}+05$ person-mrem for the uranium overburden

Table D.3-3. Individual doses and health effects from storage or disposal of diffuse NORM.

Exposure Scenario	Uranium Overburden	Phosphate Waste	Phosphate Fertilizer	Coal Ash	Water Treatment Sludge -- Fertilizer	Water Treatment Sludge -- Landfill	Mineral Processing Waste	Oil & Gas Scale/Sludge	Geothermal Waste
Onsite - Direct Gamma									
Dose (mrem/yr) ^a	2.9E+02	4.5E+02	2.8E-02	7.4E+01	1.0E+01	3.6E+00	6.9E+02	3.0E+03	3.0E+02
Health Effects ^d	1.1E-04	1.8E-04	1.1E-08	2.9E-05	4.0E-06	1.4E-06	2.7E-04	1.2E-03	1.2E-04
CPG - Direct Gamma									
Dose (mrem/yr) ^a	8.9E+01	1.4E+02	8.5E-03	2.3E+01	3.1E+00	1.1E+00	2.1E+02	9.0E+02	9.3E+01
Health Effects ^d	3.5E-05	5.3E-05	3.3E-09	8.8E-06	1.2E-06	4.3E-07	8.2E-05	3.5E-04	3.6E-05
CPG - Dust Inhalation									
Dose (mrem) ^b	2.7E-02	4.9E-03	1.7E-05	2.0E-03	1.5E-04	6.1E-05	6.6E-02	3.6E-03	2.1E-03
Health Effects ^d	4.2E-09	7.5E-10	2.6E-12	3.0E-10	2.3E-11	9.5E-12	1.0E-08	5.6E-10	3.2E-10
NORM in Building Materials									
Dose (mrem/yr) ^a	--	1.1E+04	--	1.9E+03	--	--	1.7E+04	--	--
Health Effects ^d	--	4.4E-03	--	7.3E-04	--	--	6.7E-03	--	--
Drink Contaminated Well Water									
Dose (mrem) ^c	5.7E-03	1.3E-01	1.2E-07	6.2E-01	2.6E-05	8.0E-06	3.3E-03	1.8E+00	1.4E-01
Health Effects ^d	8.7E-10	2.1E-08	1.9E-14	9.6E-08	4.0E-12	1.2E-12	5.2E-10	2.9E-07	2.1E-08
Foodstuffs Contaminated by Well Water									
Dose (mrem) ^c	8.6E-03	2.0E-01	1.8E-07	9.5E-01	4.0E-05	1.2E-05	5.1E-03	2.8E+00	2.1E-01
Health Effects ^d	1.3E-09	3.2E-08	2.8E-14	1.5E-07	6.2E-12	1.9E-12	7.9E-10	4.4E-07	3.3E-08
Foodstuffs Contaminated by Dust Deposition									
Dose (mrem) ^c	4.6E-07	2.5E-07	1.0E-10	3.2E-08	1.5E-08	5.9E-09	7.7E-07	3.2E-07	2.5E-07
Health Effects ^d	7.1E-14	3.8E-14	1.6E-17	4.9E-16	2.3E-16	9.1E-16	1.2E-13	4.9E-14	3.8E-14
Foodstuffs from Fertilized Soil									
Dose (mrem) ^c	--	--	5.5E-04	--	6.6E-02	--	--	--	--
Health Effects ^d	--	--	8.5E-11	--	1.0E-08	--	--	--	--

a The annual whole body effective dose equivalent (mrem/yr).

b The 50-year committed dose equivalent (mrem) from one year of intake.

c The 50-year committed dose equivalent (mrem) from one year of uptake.

d The 70-year lifetime risk of a fatal cancer from one year of exposure.

Table D.3-4. Population doses and health effects from storage or disposal of diffuse NORM.

Exposure Scenario	Uranium Overburden	Phosphate Waste	Phosphate Fertilizer	Coal Ash	Water Treatment Sludge -- Fertilizer	Water Treatment Sludge -- Landfill	Mineral Processing Waste	Oil & Gas Scale/Sludge	Geothermal Waste
Exposure to Resuspended Particulates									
Dose (person-mrem) ^a	2.4E+02	2.7E+02	4.8E-01	5.0E+01	4.1E+00	3.2E-01	1.7E+02	5.6E+00	6.7E+00
Health Effects ^b	3.7E-05	4.4E-05	7.5E-08	7.9E-06	7.3E-07	5.5E-08	2.7E-05	9.8E-07	1.2E-06
River Water Contaminated by Groundwater									
Dose (person-mrem) ^a	1.0E+01	2.9E+03	9.0E-04	3.7E+03	1.7E-01	7.1E-03	5.9E-01	2.7E+02	1.7E+01
Health Effects ^b	1.5E-06	4.5E-04	1.4E-10	5.8E-04	2.6E-08	1.1E-09	9.1E-08	4.2E-05	2.7E-06
River Water Contaminated by Surface Runoff									
Dose (person-mrem) ^a	1.1E+05	2.3E+05	6.3E+00	5.4E+04	1.0E+03	5.1E+01	1.7E+04	3.6E+04	4.9E+04
Health Effects ^b	1.7E-02	3.5E-02	9.8E-07	8.3E-03	1.6E-04	7.9E-06	2.6E-03	5.6E-03	7.6E-03
Foodstuffs from Fertilized Soil									
Dose (person-mrem) ^a	--	--	2.7E+00	--	3.2E+02	--	--	--	--
Health Effects ^b	--	--	4.2E-07	--	5.0E-05	--	--	--	--

^a The 50-year committed dose equivalent to the exposed population from one year of intake (uptake). The number of persons in the exposed population is given in Table D.2-3.

^b The number of excess fatal cancers expected in the exposed population as a result of one year of exposure. The number of persons in the exposed population is given in Table D.2-3.

NORM sector to 6.3 person-mrem for the phosphate fertilizer NORM sector. The corresponding cumulative health effects to the exposed populations range from 1.7E-02 for uranium overburden to 9.8E-07 for phosphate fertilizer.

3.4 BENCHMARKING THE DOSE METHODOLOGY

CPG doses from two exposure scenarios were also calculated with the PRESTO-CPG-PC code (EPA89b) as a benchmark for the dose equations used in the present analysis. PRESTO-CPG-PC was used instead of PATHRAE because it represents a more independent check on the calculated doses. The two exposure scenarios calculated with PRESTO are well water ingestion and dust inhalation of radionuclides from disposed oil and gas production scales and sludges. Insofar as possible, PRESTO used the input parameters given in section D.2.3. The resulting doses are given by scenario and nuclide in Table D.3-5. The major differences in the well water ingestion results are due to differences in leach rates. The major differences in the dust inhalation results are due to vastly different resuspension rates. If the PRESTO resuspension rates are increased to equal those from the simple formalism, the inhalation doses are also different by a factor of about three.

3.5 SUMMARY AND CONCLUSIONS

Estimated dominant risks to workers at NORM storage and disposal sites are summarized in Table D.3-6. For disposal pile workers, the dominant exposure pathway is direct gamma exposure. 70-year lifetime risks from one year of exposure range from 2.5E-04 for the oil and gas scale/sludge NORM sector to 2.4E-09 for workers on fields repeatedly fertilized with phosphate fertilizer. Health risks to office workers exposed to indoor radon inhalation are significantly higher than health risks to disposal pile workers. For indoor radon inhalation, 70-year lifetime risks from one year of exposure range from 9.3E-02 for the geothermal waste sector to 1.2E-04 for landfill disposal of water treatment sludge.

Table D.3-5. Benchmark of methodology for oil and gas scale/sludge.

<u>Nuclide</u>	<u>Simple Methodology Dose (mrem/yr)</u>	<u>PRESTO Dose (mrem/yr)</u>	<u>Simple PRESTO</u>
Well Water Ingestion			
Po-210	4.7E-01	7.8E-01	0.60
Pb-210	1.4	4.7	0.30
Dust Inhalation			
Po-210	2.2E-04	1.1E-06	200
Pb-210	3.3E-04	5.9E-07	559
Ra-226	2.0E-04	2.2E-06	91
Th-228	2.8E-03	2.0E-05	140

Table D.3-6. Summary of dominant risks to workers from one year of exposure.

Waste Sector	Disposal Pile Worker		Office Worker	
	Health Effects^a	Dominant Pathway	Health Effects^a	Dominant Pathway
Uranium Overburden	2.5E-05	Direct Gamma	1.8E-02	Radon Inhalation
Phosphate Waste	3.8E-05	Direct Gamma	1.2E-02	Radon Inhalation
Phosphate Fertilizer	2.4E-09	Direct Gamma	--	--
Coal Ash	6.3E-06	Direct Gamma	1.4E-04	Radon Inhalation
Water Treatment Sludge -- Fertilizer	8.8E-07	Direct Gamma	--	--
Water Treatment Sludge -- Landfill	3.1E-07	Direct Gamma	1.2E-04	Radon Inhalation
Mineral Processing Waste	5.9E-05	Direct Gamma	2.7E-02	Radon Inhalation
Oil & Gas Scale/Sludge	2.5E-04	Direct Gamma	2.1E-02	Radon Inhalation
Geothermal Waste	2.6E-05	Direct Gamma	9.3E-02	Radon Inhalation

a The 70-year lifetime risk of a fatal cancer from one year of exposure.

Estimated dominant risks to members of the CPG are summarized in Table D.3-7. The table shows maximum health risks from exposure pathways exclusive of radon inhalation and health risks from radon inhalation pathways. For exposure pathways exclusive of radon inhalation the dominant CPG health risks are from direct gamma exposure, either to a person assumed to live onsite at an abandoned disposal site or from exposure to NORM in building materials. 70-year lifetime risks from one year of exposure range from $6.7\text{E-}03$ for the mineral processing waste NORM sector to $1.1\text{E-}08$ for a field repeatedly fertilized with phosphate fertilizer. For radon inhalation, the dominant CPG health risks are estimated to result from indoor exposure to radon by a person living onsite at an abandoned site. 70-year lifetime risks from one year of exposure to indoor radon are estimated to be one or two orders of magnitude higher than risks from direct gamma exposure, ranging from $3.1\text{E-}01$ for the geothermal waste sector to $3.0\text{E-}06$ for a field repeatedly fertilized with phosphate fertilizer.

Estimated population health effects (e.g., cumulative health effects to persons living offsite) are shown in Table D.3-8 for the reference site and in Table D.3-9 for the total U.S. population impacted by each NORM sector. The largest number of cumulative health effects is associated with the coal ash NORM sector, in part because of the large number of sites required to deplete the total 20-year inventory. Two of the NORM sectors have total population health effects equal to or greater than unity. The sectors with the lowest total population health effects are water treatment sludge, oil and gas scale/sludge, and geothermal waste, each having 0.1 health effects or less from one year of exposure.

The risk assessment results suggest that a relatively moderate number of health effects could result from the improper use or disposal of diffuse NORM wastes. The risk assessment results indicate that less than 20 lifetime health effects could occur to the total population from one year of exposure to diffuse NORM. The dominant NORM sectors from a population health risk standpoint are coal ash and mineral processing wastes.

These results are based only on the total NORM waste volume generated over the next 20 years. It is anticipated that should the total inventory of NORM wastes accumulated to date be used instead, the total number of health effects would certainly increase significantly. However, this assumption would most likely be unrealistic because the accumulated waste inventory is not in a readily accessible and useable form, as postulated in this report, and

Table D.3-7. Summary of dominant risks to the critical population group from one year of exposure.

Waste Sector	Exposure Pathways Except Radon Inhalation		Radon Inhalation	
	Health Effects^a	Dominant Pathway	Health Effects^a	Dominant Pathway
Uranium Overburden	1.1E-04	Onsite -- Direct Gamma	6.0E-02	Onsite -- Indoor Exposure
Phosphate Waste	4.4E-03	NORM in Building Materials	3.9E-02	Onsite -- Indoor Exposure
Phosphate Fertilizer	1.1E-08	Onsite -- Direct Gamma	3.0E-06	Onsite -- Indoor Exposure
Coal Ash	7.3E-04	NORM in Building Materials	4.5E-04	Onsite -- Indoor Exposure
Water Treatment Sludge -- Fertilizer	4.0E-06	Onsite -- Direct Gamma	1.0E-03	Onsite -- Indoor Exposure
Water Treatment Sludge -- Landfill	1.4E-06	Onsite -- Direct Gamma	3.8E-04	Onsite -- Indoor Exposure
Mineral Processing Waste	6.7E-03	NORM in Building Materials	8.9E-02	Onsite -- Indoor Exposure
Oil & Gas Scale/Sludge	1.2E-03	Onsite -- Direct Gamma	7.0E-02	Onsite -- Indoor Exposure
Geothermal Waste	1.2E-04	Onsite -- Direct Gamma	3.1E-01	Onsite -- Indoor Exposure

^a The 70-year lifetime risk of a fatal cancer from one year of exposure.

Table D.3-8. Summary of cumulative health effects per reference site from one year of exposure.

Waste Sector	Health Effects^a	Dominant Pathway
Uranium Overburden	1.7E-02	River Water Contaminated by Surface Runoff
Phosphate Waste	3.5E-02	River Water Contaminated by Surface Runoff
Phosphate Fertilizer	9.8E-07	River Water Contaminated by Surface Runoff
Coal Ash	8.9E-03	River Water Contaminated by Surface Runoff
Water Treatment Sludge -- Fertilizer	1.6E-04	River Water Contaminated by Surface Runoff
Water Treatment Sludge -- Landfill	7.9E-06	River Water Contaminated by Surface Runoff
Mineral Processing Waste	2.6E-03	River Water contaminated by Surface Runoff
Oil & Gas Scale/Sludge	5.6E-03	River Water Contaminated by Surface Runoff
Geothermal Waste	7.6E-03	River Water Contaminated by Surface Runoff

a Number of excess fatal cancers (70-year lifetime risk) expected in the exposed population as a result of one year of exposure. The number of persons in the exposed population per reference site is given in Table D.2-3.

Table D.3-9. Summary of cumulative health effects in the United States from one year of exposure.

Waste Sector	Number of Sites for 20-Year Inventory	Health Effects^a
Uranium Overburden	1.4E+01	2.4E-01
Phosphate Waste	1.5E+01	5.2E-01
Phosphate Fertilizer	9.4E+05	9.2E-01
Coal Ash	1.3E+03	1.2E+01
Water Treatment Sludge -- Fertilizer	4.4E+02	7.0E-02
Water Treatment Sludge -- Landfill	2.3E+02	1.8E-03
Mineral Processing Waste	6.7E+02	1.7E+00
Oil & Gas Scale/Sludge	1.0E+01	5.6E-02
Geothermal Waste	2.0E+00	1.5E-02

a The number of excess fatal cancers (70-year lifetime risk) expected in the total U.S. population as a result of one year of exposure.

currently there is no outlet which would allow that much NORM waste to be recycled.

Given the uncertainties associated with waste volumes, radionuclide concentrations, and exposure pathway models and parameters, it is estimated that the results of this risk assessment analysis are within a factor of 3 of results obtained when using more sophisticated computer codes. In general, it is suspected that the variability of the results is asymmetric, in the sense that the degree of conservatism is more pronounced on the lower range of the input parameters and assumptions than on the higher end. Accordingly, depending upon a specific input parameter or assumption, the results may reveal a still greater degree of variability. Finally, it should be noted that changing a parameter does not always yield results that are directly proportional since competing factors may nullify an increase in a specific parameter.

These NORM waste risk assessments are based on relatively simple models that incorporate a number of assumptions, some better defined than others. Thus the results incorporate some uncertainty. The results imply, however, that the number of potential health effects associated with some NORM sectors may be significant enough to warrant more detailed modeling of NORM waste storage and disposal practices in order to further refine the risk assessment analysis.

CHAPTER D REFERENCES

- EPA87a** U.S. Environmental Protection Agency, "PATHRAE-EPA: A Performance Assessment Code for the Land Disposal of Radioactive Wastes, Documentation and Users Manual," Office of Radiation Programs, EPA 520/1-87-028, December 1987.
- EPA87b** U.S. Environmental Protection Agency, "PRESTO-EPA-POP: A Low-Level Radioactive Waste Environmental Transport and Risk Assessment Code, Volume I, Methodology Manual," Office of Radiation Programs, EPA 520/1-85-001, draft, November 1987.
- EPA88a** U.S. Environmental Protection Agency, "Low-Level and NARM Radioactive Wastes, Draft Environmental Impact Statement for Proposed Rules, Volume 1, Background Information Document," EPA 520/1-87-012-1, June 1988.
- EPA88b** U.S. Environmental Protection Agency, "Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion," EPA-520/1-88-020, September 1988.
- EPA89a** U.S. Environmental Protection Agency, "Risk Assessment Methodology, Environmental Impact Statement for NESHAPS Radionuclides, Volume 1, Background Information Document," EPA 520/1-89-005, September 1989.
- EPA89b** U.S. Environmental Protection Agency, "A PC Version of the PRESTO-EPA-CPG Operation System," EPA 520/1-89-017, April 1989.
- NRC87** U.S. Nuclear Regulatory Commission, "Methods for Estimating Radioactive and Toxic Airborne Source Terms for Uranium Milling Operations," Regulatory Guide 3.59, March 1987.
- ROG85** Rogers, V.C. et al., "The PATHRAE-T Performance Assessment Code for Analyzing Risks From Radioactive Wastes," Rogers and Associates Engineering Corp. report to U.S. Department of Energy, RAE-8339/12-2, December 1985.

E. CONCLUSIONS AND RECOMMENDATIONS

E.1 CONCLUSIONS

The Environmental Protection Agency (EPA), in September 1989, developed a preliminary risk assessment characterizing generation and disposal practices of wastes which contain diffuse levels of naturally-occurring radioactive materials (NORM). Such wastes are typically generated in large volumes of potentially recyclable materials which contain Ra-226 at elevated concentrations. The preliminary risk assessment report was prepared as an initial step in the development of acceptable standards governing the disposal and re-use of NORM waste and material. These bulk wastes and materials are of such large volume and relatively low radionuclide concentrations that it was deemed inappropriate to include them within the scope of other proposed rulemaking activities. The preliminary report indicated that there exists a need to further review the data, assumptions, and models used in that report, provide additional information on categories of diffuse NORM wastes which were not explicitly addressed, and perform a more detailed risk assessment. This report, prepared in response to these recommendations, presents the results of further characterization efforts and a revised risk assessment analysis.

All soils and rocks are known to contain some amounts of naturally-occurring radioactive material (NORM). The major radionuclides are uranium and thorium, and their respective decay products. One of the decay products is radium (Ra-226) and its daughters products, which are the principal radionuclides of concern in characterizing the redistribution of radioactivity in the environment. Radium is normally present in soil in trace concentrations of about one picocurie per gram (pCi/g).

Certain processes, however, tend to reconcentrate or enrich the radioactivity to much higher levels in the resulting waste or by-product materials. The concentration of radium in wastes can vary considerably and primarily depends upon the initial levels and processes reconcentrating the radium. Such processes include mining and beneficiation, mineral processing, coal combustion, the treatment of drinking water, among others. Some of the NORM wastes or materials are being generated in large quantities and typically disposed or

stored at the point of generation. At times, however, NORM material and waste are used in various applications which may result in unnecessary radiation exposures, potential adverse health effects, or environmental contamination.

NORM waste generation and disposal practices were characterized for eight NORM sectors. The largest inventories of NORM wastes are associated with mineral processing, phosphate rock production, uranium mining, and coal combustion from utility and industrial boilers. Each of these processes generate large volumes of waste with annual production rates of several million metric tons. Over the next 20 years, these NORM sectors will generate significant waste inventories ranging from about 1 to 20 billion metric tons. Smaller quantities of waste are generated by the petroleum industry (oil and gas pipe scale) and by drinking water treatment facilities. It is anticipated that water treatment facilities and the petroleum industry will generate 6 and 13 million metric tons of waste over the next 20 years, respectively. Phosphate fertilizers, while not a waste, are included in this analysis because of their elevated radium concentrations. It is estimated that about 100 million metric tons of fertilizers will be applied in agricultural fields over the next 20 years.

It should be noted that these estimates incorporate a large degree of uncertainty since the characterization of these NORM sectors is based on limited information and data (see the next section for further details on this aspect). It was also concluded that for some NORM sectors, waste generation and disposal practices were partially represented or that the available information was deemed to be inadequate or incomplete. Accordingly, there is a need to better characterize the radiological and physical properties of these wastes, evaluate NORM waste disposal and application practices, and refine waste generation rate estimates.

The risk assessment analyses addresses several exposure pathways to the public and to workers for each of the eight NORM sectors. Such pathways include direct radiation exposures while standing on NORM waste or material, standing at a hypothetical facility fence post, and due to the incorporation of waste in building materials. Inhalation exposures are due to resuspended airborne particulates and radon emissions from waste piles. Indoor radon in structures is also considered for homes erected over waste and incorporating NORM in building materials.

For internal exposure, this assessment considers the drinking of ground and surface water, consumption of vegetables and fruits, and the ingestion of animal products (meat and milk). The risk assessment assumes that the water and foodstuff contain residual levels radioactivity. In water, it is assumed that waste leachates have contaminated ground and surface water sources. All water needs are assumed to be supplied from a well or surface stream, including domestic and agricultural uses. Vegetables and fruits are assumed to be grown in soils containing NORM waste and livestock are assumed to be grazing in contaminated pastures.

The results reveal that for the Critical Population Group (CPG), six NORM sectors dominate with annual non-radon risks ranging from 1.1×10^{-4} to 6.7×10^{-3} . These sectors, in a decreasing order of risks, are mineral processing waste, phosphate waste, oil and gas scale, coal ash, geothermal waste, and uranium overburden. The remaining sectors are characterized by annual risks which are less than 6.0×10^{-6} . The dominant exposure pathways associated with these risks include direct radiation from the use of NORM wastes in building materials, and while standing on NORM wastes, or at the fence post. In terms of indoor radon exposures, all NORM sectors except phosphate fertilizer dominate with annual risks ranging from 0.31 to 3.8×10^{-4} . The phosphate fertilizer NORM sector has a resulting annual CPG risk of 3.0×10^{-6} . In the aggregate, the CPG risks associated with all ingestion exposure pathways are typically 10^{-6} or less. The annual risks due to downwind radon exposures are less than 10^{-7} across all NORM sectors.

The risks to disposal pile workers range from 2.5×10^{-4} for the oil and gas scale sector to 2.4×10^{-9} for the phosphate fertilizer sector. For office workers, the risks are mainly from radon daughter inhalation and range from 9.3×10^{-2} for geothermal waste to 1.2×10^{-4} for water treatment sludge.

The number of population health effects at each generic site, ranges from 3.5×10^{-2} to 7.9×10^{-6} . In decreasing order of potential number of health effects, the NORM sectors are phosphate waste, uranium overburden, coal ash, geothermal waste, oil and gas scale, mineral processing, water treatment, and phosphate fertilizers. The dominant exposure pathway is radon for four of the seven NORM sectors. Ingestion of well water (for both, oil and gas scale, and coal ash) and foodstuff (for phosphate fertilizers) are the controlling pathways for the remaining three NORM sectors. The potential number of health effects due to downwind

radon exposure ranges from 3.5×10^{-2} to 5.5×10^{-8} . In decreasing order of potential number of health effects, these NORM sectors are phosphate waste, uranium overburden, mineral processing waste, oil and gas scale, coal ash, water treatment sludge, and phosphate fertilizers.

The risk assessment results suggest that a relatively moderate number of health effects could result from the improper use or disposal of diffuse NORM wastes. The risk assessment results indicate that about 30 population health effects could occur from exposures received over the next 20 years, with some individual risks as high as 3 in a 1000. The dominant NORM sectors and their respective health effects are phosphate fertilizers with 17, mineral processing with 2, coal ash with 12, and water treatment sludge with 1. These results are based only on the total NORM waste volume generated over the next 20 years. It is anticipated that should the total inventory of NORM wastes accumulated to date be used instead, the total number of health effects would certainly increase significantly. However, this assumption would most likely be unrealistic because the accumulated waste inventory is not in a readily accessible and useable form, as postulated in this report, and currently there is no outlet which would allow that much NORM waste to be recycled.

Given the uncertainties associated with waste volumes, radionuclide concentrations, and exposure pathway model and parameters, it is estimated that the results of this risk assessment analysis are within a factor of 3 of results obtained when using more sophisticated computer codes. In general, it is suspected that the variability of the results is asymmetric, in the sense that the degree of conservatism is more pronounced on the lower range of the input parameters and assumptions than on the higher end. Accordingly, depending upon a specific input parameter or assumption, the results may reveal a still greater degree of variability. Finally, it should be noted that changing a parameter does not always yield results that are directly proportional since competing factors may nullify an increase in a specific parameter.

Given that these results are based on a number of assumptions, some better defined than others, these estimates are still uncertain. The results imply, however, that the number of potential health effects may be significant enough to warrant additional characterization of NORM waste generation and disposal practices in order to further refine risk assessment analysis.

Even with these uncertainties, however, it is clear that a significant number of health effects and high risks could occur for a limited number of individuals in exposed populations. Therefore, it is worth evaluating the regulatory options that exist to control NORM wastes. One option for regulating the disposal of NORM wastes would be the use of RCRA, to require disposal in RCRA hazardous waste disposal facilities. This may not be a particularly feasible option as RCRA does not now include radioactivity as a characteristic used to define hazardous wastes.

Another option with RCRA would be the use of Subtitle D requirements for regulated disposal. This option is being studied by EPA for certain mineral processing wastes, but the use of Subtitle D is less desirable, since Subtitle D lacks Federal enforcement capabilities. Another major constraint with the use of RCRA, however, is that RCRA only has authority over waste disposal. Since much of the health impact from NORM waste comes about from reuse that is not appropriate, RCRA could not be used to control that aspect since it would be considered recycling and not waste disposal.

There are currently regulations being considered which apply to the disposal of higher concentrations of NORM wastes (greater than 2,000 pCi/g). These regulations are being prepared under the authority of Section 6 of TSCA, which could also be used to regulate the diffuse NORM wastes. Under Section 6, materials found to present unreasonable risk to the public can be controlled in a variety of manners, including requirements on disposal, manufacture, distribution in commerce, and use of warning labels and record keeping.

Finally, the EPA, under the Toxic Substance and Control Act (TSCA), could assume the authority to regulate the manufacture and disposal or commercial distribution of items, materials, and waste containing NORM found to present an unreasonable public health risk. Additional requirements could involve the placement of warning labels on some items or signs in some areas and necessitate a record keeping and inventory system for specific categories of NORM material. Currently, there is an impetus to consider using TSCA to regulate higher activity NORM wastes and it may be appropriate to extend TSCA to also regulate diffuse NORM wastes as well. With TSCA, the EPA could prohibit certain use and application of NORM wastes which present unreasonable public health risks or could result in environmental contamination.

F.2 RECOMMENDATION 3

The following summarizes a number of specific recommendations based on the information and data presented in Chapter B. It is recommended that in subsequent efforts these aspects be considered in refining and updating the existing characterization of each NORM sector and risk assessment analyses. It should be noted that these recommendations, as discussed below, are not all comprehensive, but are included here for illustrative purposes and to give a sense of perspective on the type and scope of the uncertainties associated with the results of this analysis. The reader is referred to Chapter B for more details regarding each NORM sector.

F.2.1 Waste Volumes and Characteristics

For some of the eight NORM sectors, there is a need to further characterize waste volumes and generation rates. In some cases, the assumed amount of wastes contained in the pile or held in inventory may in fact represent varying fractions or multiples of yearly generation rates. There may also be some inconsistencies between the volume of NORM waste assumed to be stored at a site and the yearly average quantity based on current practices and projections. The amounts and total waste inventory stored at any one site is known to vary since some wastes are always added and subjected to waste management procedures. Because of this dynamic process, it may be in fact difficult to define a generic site which is representative of a specific NORM sector. It should also be noted that in some instances, because of a declining industry or business, the projected 20-year waste inventory is dwarfed by the total amount of waste already stockpiled from past activities. It may just be that any additional waste which will be generated over the next 20 years, in itself, does not present a significantly greater degree of risk when compared to the risks associated with existing inventories. Accordingly, there is a need to determine if a specific NORM sector or site should be considered under the umbrella of reclamation program, or fall under the jurisdiction of future NORM regulations. A threshold, based on yearly waste generation rates and existing waste inventories, could perhaps define the category (either reclamation or subject to proposed NORM regulations) in which a NORM sector or site belongs.

It was noted that NORM wastes may be used in several types of applications, from building and construction materials to consumer products. Because of the bulk quantities, there is a need evaluate, based on a survey, the mobility of this material from the point of generation to the point of processing, use, or manufacturing, including amounts of wastes used or incorporated in building materials at the local and regional or national level. For example, what are the technical and economic factors which may lead a specific user to select one NORM waste generator among others? Are there threshold quantities below which the transportation costs outweigh the cost of the material itself? Such considerations may reveal that perhaps the bulk the waste is simply not used or, if so, only in limited quantities and within the locality in which they are produced. Consequently, there may be a limit in the rate of utilization of NORM wastes. Should this be the case, the profile of the population risks and health effects may shift from what may have been perceived as exposures to distant end-users to only a very few nearby site residents. The potential health risks may then be confined to short distances around each waste generator. Some sources of information and data which may help answering these questions, as well as others, include the upcoming results of the American Water Works Association 1989 survey of water utilities, the federal reporting data system of water utilities, and the American Petroleum Institute NORM data bank.

Another point which needs to be examined in greater depth, given the physical characteristics of such wastes, is the potential re-use limited to only a few application? If so, there is a need to reevaluate the risk assessment models to ensure that the exposure pathways being considered are indeed realistic with current or anticipated applications. For example, in considering uranium overburden, would such material be used as backfill or for land reclamation on large scale given that mining sites are typically located in arid and remote regions of the U.S.? Similarly, are certain NORM wastes suitable for incorporation in construction materials? For example, wastes which have been subjected to chemical extraction or processing may have physical properties which make them less desirable than other competing materials. Conceivably, such wastes will have a narrower range of applications and, hence, a limited number of potential exposure pathways.

F.2.2 Radiological Source Term

This report has identified that, for any given NORM sector, it is not uncommon for radionuclide concentrations to vary by several orders of magnitude. This variation is primarily due to two factors: 1) the natural variability of radionuclide concentrations in any materials, and 2) processes or practices which are specific to a NORM sector. The wastes generated by some of the sectors is poorly understood because of the paucity of the data. The literature contains only a few studies and in most cases, a few specific sites were evaluated for each waste form. In addition, the characterization of some of the industries was based on very limited field sampling and analysis programs, with a limited number of samples taken at each site and in some instances none at all. It is generally believed by geologists that the presence of naturally-occurring radioactivity is more dependent upon the geological formation or region than a particular type of mineral ore. It will also be apparent that ores often contain many different minerals. Accordingly, it cannot be assumed that the radionuclide content of one type of ore and its associated wastes will be representative of a NORM sector or industry.

The quantity of waste materials and their physical and radiological characteristics differ widely among the various NORM sectors. In addition, depending on the processing or treatment methods employed, some of the resulting wastes can contain elevated concentrations of naturally-occurring radionuclides. Furthermore, materials stockpiled at any one site are not always necessarily waste. Some of the wastes are in fact additional resources which may be subjected to further processing to extract additional minerals.

There have been reports that some of the more uncommon metals have highly radioactive waste products. Also, some of the processes associated with metal extraction appear to highly concentrate the radionuclides and enhance their environmental mobility. Some published information and data to support these arguments have been presented, but in most cases it is suggested that further studies be conducted prior to reaching any conclusions.

In considering the presence of radioactivity, there is a need to refine the relationship between waste volumes and radionuclide concentrations. The existing assessment relies on average concentrations. It is, however, suspected that concentrations are log-normally

distributed and that the bulk volume is primarily characterized by very low concentrations. Furthermore, this assessment noted that for some mineral processing wastes, some ores (e.g., copper) may contain uranium in elevated concentrations (at milling grade) which are equivalent to those found in uranium mines. Such findings, if confirmed, may have a significant impact on the results and conclusions in the next risk assessment. With respect to waste forms there is also a need to reevaluate the physical characteristics of the waste since this information is used to model the radiological source terms and environmental transport and mobility. For example, the following items, among others, need to be re-examined: waste permeability, particle size vs. specific activity, porosity, hydraulic conductivity, leach rate or coefficient of distribution (K_d).

F.2.3 Environmental Transport Mechanisms

The current analyses consider several transport mechanisms by which NORM materials or wastes could become a potential source of exposures. These transport mechanisms include the re-use of NORM wastes into building materials, introduction of NORM materials in construction activities, application of such wastes as soil conditioners, atmospheric dispersion, and the infiltration of waste leachates in ground water aquifers and surface streams. A last category, although not truly an environmental transport mechanism, addresses direct radiation exposures, to the nearby resident, due to the presence of the wastes either stored in piles or spread in soils and agricultural fields.

This risk assessment assumes that the bulk of the material is used in its basic form, for example, unprocessed and as an additive or as clean fill. It should be noted that some industrial sectors are processing such wastes for mineral resources recovery or as feedstock for other types of products. It is suspected that additional processing may create a substream of industrial wastes whose radiological properties are unknown. The commercial end product may also have radiological properties which may or may not pose a public health risk. This type of intermediate application or processing across several industrial sectors may result in the generation of new waste streams and other forms of waste disposal practices.

F.2.4 Exposure Pathways

The risk assessment analyses addressed several exposure pathways for each of the eight NORM sectors. Such pathways include direct radiation exposures while standing on NORM waste or material, standing at a hypothetical facility fence post, and due to the incorporation of waste in building materials. Inhalation exposures are due to resuspended airborne particulates and radon emissions from waste piles. Indoor radon in structures is also considered for homes erected over waste and incorporating NORM in building materials.

For internal exposure, this assessment considers the drinking of ground and surface water, consumption of vegetables and fruits, and the ingestion of animal products (meat and milk). The risk assessment assumes that the water and foodstuff contain residual levels radioactivity. In water, it is assumed that NORM waste leachates have contaminated ground and surface waters. All water needs are assumed to be supplied from a ground water well or surface stream, including domestic and agricultural uses. Vegetables and fruits are assumed to be grown in soils containing NORM waste and livestock are assumed to be grazing in contaminated pastures.

The exposure pathways selected for this assessment are comprehensive and are in agreement with similar studies performed by the EPA and others. It is currently envisioned that no new pathways need to be considered unless currently unforeseen mode of exposures are identified as a results of additional investigation. Consequently, should any a new risk assessment analyses be required, existing model parameters should be refined to more accurately represent each exposure pathway.

F.2.5 Exposed Populations

Exposed populations include workers, the critical population group (CPG) and the general population in the vicinity of the disposal sites. The analyses consider the states in which a NORM site might be located, where the waste material might be used or applied, population densities near each site, location of the nearby resident, and an average type of residence.

As was noted earlier, the size of the exposed population may be dependent upon the utilization rate of any specific NORM waste. Should this be the case, the profile of the exposed population may then shift to nearby residents rather than distant end-users. The potential health risks may then be confined to short distances around each waste generator. In assessing the potential number of health effects, there may also be a need to consider expressing these results as waste volume weighted averages, which would take into account waste generation rates or existing inventories and the size of the exposed population.

There is also a need to refine the connection between exposure pathways and the size of the exposed population. For example, when considering the ingestion of contaminated vegetables and animal food by-products, it may be unrealistic to assume that a NORM site could impact a food supply which cannot be produced in the immediate surroundings or fulfil the needs of large population centers. For example, in considering sites located in arid and remote regions of the southwest, it is highly improbable that a large population segment would be impacted by a metal mining and processing facility.

F.2.6 Evaluation of Overall Uncertainties

The assumptions and information used in this risk assessment analysis were reviewed and, for each NORM sector, the parameters and assumptions were examined, and ranked as to their level of uncertainty. For each exposure pathway, this review considered each NORM sector and waste, radiological source terms, environmental transport mechanisms, types of exposure pathways, and exposed populations.

A simple ranking system is used to attach a level of priority to the identified parameters. The ranking process reflects information gathered to date, literature review, and technical judgement. For this exercise, a simple numerical ranking scheme is used, for example, a value of 1 to characterize a parameter with the least uncertainty and 5 for one with the most. Table F.2-1 presents the results of this ranking process. From this tabulation, the following conclusions are reached:

- The ranking each NORM sector, in a decreasing order of uncertainty, is as follows: 1) mineral processing, 2) petroleum pipe scale, 3) water treatment,

Table E.2-1. Sources and pathways uncertainties ranking.^(a)

<u>Item</u>	<u>Uranium Ovrbrdn</u>	<u>Phosph.</u>	<u>Fert.</u>	<u>Coal Ash</u>	<u>Petrol. Scales</u>	<u>Water Treat.</u>	<u>linar. l roces.</u>
Wastes:							
Sites	1	1	NA	2	3	3	3
Volumes	2	1	2	2	3	3	4
Forms	2	1	2	1	3	3	4
Propert.	2	1	3	2	2	3	4
Config.	3	1	NA	2	4	3	3
Disposal	2	1	NA	1	3	2	4
Uses	3	2	1	2	3	2	4
Radiological:							
Nuclides	2	2	2	1	1	3	3
Concent.	2	2	2	1	2	3	3
Propert.	2	2	2	2	3	3	4
Environmental Transp.:							
Disposal	2	2	NA	2	3	2	3
Applctn.	3	3	1	3	3	2	4
Atmosph.	3	2	2	2	3	2	2
Surf. H ₂ O	3	2	2	2	3	2	2
Grnd. H ₂ O	4	2	2	2	3	2	2
Exp. Pathways:							
Inhalatn.	1	1	1	1	2	1	2
Ext. Rad.	1	1	2	3	3	4	4
Ingestion	1	1	1	1	2	1	2
Population:							
Sites	2	1	1	3	3	2	3
Pop. Dens.	2	1	1	3	3	2	3
CPG	2	2	2	2	4	2	4
MGP	2	2	2	2	4	2	4
SUM:	46	34	31	42	63	52	71

(a) Ranking system reflects information gathered to date, literature survey, and technical judgment. For example, a value of 1 characterizes a parameter with the least uncertainty and a value of 5 for the one with the most.

4) uranium overburden, 5) coal ash, 6) phosphate waste, and 7) phosphate fertilizers.

- Three NORM sectors stand-out as requiring further evaluation, these are mineral processing, water treatment, and petroleum oil/gas scale.
- For two NORM sectors, the ranking scheme indicates that the information gathered to date is sufficiently detailed for the purpose of this risk assessment. These 2 NORM sectors include, uranium overburden and coal ash. It may still be necessary to revisit these two NORM sectors for the purpose of updating some of the descriptive sector parameters and revise the risk assessment analysis.
- The phosphate waste and fertilizer NORM sectors are deemed to be adequately characterized, but may nevertheless require some further analysis simply for the purpose of refining the risk assessment analysis.

APPENDIX A

TABULATIONS OF DOSE AND RISK CALCULATIONS TO CHAPTER D

W1a

**WORKER - DIRECT GAMMA EXPOSURE
for: Uranium Overburden**

$$G = 1.10E-01$$

$$S = 1.33E+05$$

$$D(\text{mrem}) = G \cdot S \cdot C \cdot \text{DFG}$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot \text{RFG}$$

Nuclide	C	DFG	RFG	D	R
Po-210	1.66E+01	8.55E-10	3.30E-16	2.08E-04	8.01E-11
Pb-210	1.66E+01	2.91E-07	1.10E-13	7.07E-02	2.67E-08
Ra-226	2.37E+01	1.67E-04	6.50E-11	5.79E+01	2.25E-05
Th-228	1.00E+00	3.37E-04	1.30E-10	4.93E+00	1.90E-06
Ra-228	1.00E+00	9.04E-05	3.50E-11	1.32E+00	5.12E-07
Th-230	2.37E+01	8.88E-08	3.50E-14	3.08E-02	1.21E-08
Th-232	1.00E+00	6.56E-08	2.60E-14	9.60E-04	3.80E-10
U-234	2.37E+01	8.00E-08	3.10E-14	2.77E-02	1.07E-08
U-238	2.37E+01	6.41E-08	2.50E-14	2.22E-02	8.67E-09
U-235	1.20E+00	1.67E-05	6.50E-12	2.93E-01	1.14E-07
TOTAL				6.46E+01	2.51E-05

W1b

**WORKER - DIRECT GAMMA EXPOSURE
for: Phosphate Waste**

**G= 1.10E-01
S= 1.59E+05**

**D(mrem) = G * S * C * DFG
R(fatal cancers) = G * S * C * RFG**

Nuclide	C	DFG	RFG	D	R
Po-210	2.64E+01	8.55E-10	3.30E-16	3.95E-04	1.52E-10
Pb-210	2.64E+01	2.91E-07	1.10E-13	1.34E-01	5.08E-08
Ra-226	3.30E+01	1.67E-04	6.50E-11	9.64E+01	3.75E-05
Th-228	2.70E-01	3.37E-04	1.30E-10	1.59E+00	6.14E-07
Ra-228	2.70E-01	9.04E-05	3.50E-11	4.27E-01	1.65E-07
Th-230	1.30E+01	8.88E-08	3.50E-14	2.02E-02	7.96E-09
Th-232	2.70E-01	6.56E-08	2.60E-14	3.10E-04	1.23E-10
U-234	6.20E+00	8.00E-08	3.10E-14	8.68E-03	3.36E-09
U-238	6.00E+00	6.41E-08	2.50E-14	6.73E-03	2.62E-09
U-235	3.00E-01	1.67E-05	6.50E-12	8.76E-02	3.41E-08
TOTAL				9.87E+01	3.84E-05

W1c

WORKER - DIRECT GAMMA EXPOSURE
Phosphate Fertilizer

G= 1.10E-01
S= 9.66E+04

D(mrem) = G * S * C * DFG
R(fatal cancers) = G * S * C * RFG

Nuclide	C	DFG	RFG	D	R
Po-210	1.80E-03	8.55E-10	3.30E-16	1.64E-08	6.31E-15
Pb-210	1.80E-03	2.91E-07	1.10E-13	5.57E-06	2.10E-12
Ra-226	2.50E-03	1.67E-04	6.50E-11	4.44E-03	1.73E-09
Th-228	3.40E-04	3.37E-04	1.30E-10	1.22E-03	4.70E-10
Ra-228	3.40E-04	9.04E-05	3.50E-11	3.27E-04	1.26E-10
Th-230	1.60E-02	8.88E-08	3.50E-14	1.51E-05	5.95E-12
Th-232	3.10E-04	6.56E-08	2.60E-14	2.16E-07	8.56E-14
U-234	1.70E-02	8.00E-08	3.10E-14	1.45E-05	5.60E-12
U-238	1.70E-02	6.41E-08	2.50E-14	1.16E-05	4.52E-12
U-235	8.60E-04	1.67E-05	6.50E-12	1.53E-04	5.94E-11
TOTAL				6.18E-03	2.40E-09

W1d

**WORKER - DIRECT GAMMA EXPOSURE
for: Coal Ash**

G= 1.10E-01

S= 7.98E+04

D(mrem) = G * S * C * DFG

R(fatal cancers) = G * S * C * RFG

Nuclide	C	DFG	RFG	D	R
Po-210	7.00E+00	8.55E-10	3.30E-16	5.25E-05	2.03E-11
Pb-210	6.80E+00	2.91E-07	1.10E-13	1.74E-02	6.57E-09
Ra-226	3.70E+00	1.67E-04	6.50E-11	5.42E+00	2.11E-06
Th-228	3.20E+00	3.37E-04	1.30E-10	9.47E+00	3.65E-06
Ra-228	1.80E+00	9.04E-05	3.50E-11	1.43E+00	5.53E-07
Th-230	2.30E+00	8.88E-08	3.50E-14	1.79E-03	7.07E-10
Th-232	2.10E+00	6.56E-08	2.60E-14	1.21E-03	4.79E-10
U-234	3.30E+00	8.00E-08	3.10E-14	2.32E-03	8.98E-10
U-238	3.30E+00	6.41E-08	2.50E-14	1.86E-03	7.24E-10
U-235	1.60E-01	1.67E-05	6.50E-12	2.35E-02	9.13E-09
TOTAL				1.64E+01	6.33E-06

W1e

WORKER - DIRECT GAMMA EXPOSURE
for: Water Treat Sludge (Fertilizer)

$$G = 1.10E-01$$

$$S = 1.13E+05$$

$$D(\text{mrem}) = G \cdot S \cdot C \cdot \text{DFG}$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot \text{RFG}$$

Nuclide	C	DFG	RFG	D	R
Po-210	4.00E-01	8.55E-10	3.30E-16	4.25E-06	1.64E-12
Pb-210	4.00E-01	2.91E-07	1.10E-13	1.45E-03	5.47E-10
Ra-226	6.40E-01	1.67E-04	6.50E-11	1.33E+00	5.17E-07
Th-228	8.00E-03	3.37E-04	1.30E-10	3.35E-02	1.29E-08
Ra-228	8.00E-01	9.04E-05	3.50E-11	8.99E-01	3.48E-07
Th-230	8.00E-03	8.88E-08	3.50E-14	8.83E-06	3.48E-12
Th-232	8.00E-03	6.56E-08	2.60E-14	6.52E-06	2.59E-12
U-234	1.60E-01	8.00E-08	3.10E-14	1.59E-04	6.17E-11
U-238	1.60E-01	6.41E-08	2.50E-14	1.27E-04	4.97E-11
U-235	1.20E-03	1.67E-05	6.50E-12	2.49E-04	9.70E-11
TOTAL				2.26E+00	8.79E-07

W11

WORKER DIRECT GAMMA EXPOSURE
for: Water Treatment Sludge (Landfill)

$$C = 1.10E-01$$

$$t = 1.06E+05$$

$$D(\text{mrem}) = G \cdot S \cdot C \cdot DFG$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot RFG$$

Nuclide	C	DFG	RFG	D	R
Po-210	1.50E-0	8.55E-10	3.30E-16	1.50E-06	5.77E-13
Pb-210	1.50E-0	2.91E-07	1.10E-13	5.09E-04	1.92E-10
Ra-226	2.40E-0	1.67E-04	6.50E-11	4.67E-01	1.82E-07
Th-228	3.00E-0	3.37E-04	1.30E-10	1.18E-02	4.55E-09
Ra-228	3.00E-0	9.04E-05	3.50E-11	3.16E-01	1.22E-07
Th-230	3.00E-0	8.88E-08	3.50E-14	3.11E-06	1.22E-12
Th-232	3.00E-0	6.56E-08	2.60E-14	2.29E-06	9.09E-13
U-234	6.00E-0	8.00E-08	3.10E-14	5.60E-05	2.17E-11
U-238	6.00E-0	6.41E-08	2.50E-14	4.48E-05	1.75E-11
U-235	5.00E-0	1.67E-05	6.50E-12	9.74E-05	3.79E-11
TOTAL				7.96E-01	3.09E-07

W1g

WORKER - DIRECT GAMMA EXPOSURE
for: Mineral Processing Waste

$$G = 1.10E-01$$

$$S = 1.36E+05$$

$$D(\text{mrem}) = G \cdot S \cdot C \cdot \text{DFG}$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot \text{RFG}$$

Nuclide	C	DFG	RFG	D	R
Po-210	2.50E+01	8.55E-10	3.30E-16	3.20E-04	1.23E-10
Pb-210	2.50E+01	2.91E-07	1.10E-13	1.09E-01	4.11E-08
Ra-226	3.50E+01	1.67E-04	6.50E-11	8.74E+01	3.40E-05
Th-228	1.00E+01	3.37E-04	1.30E-10	5.04E+01	1.94E-05
Ra-228	1.00E+01	9.04E-05	3.50E-11	1.35E+01	5.24E-06
Th-230	3.50E+01	8.88E-08	3.50E-14	4.65E-02	1.83E-08
Th-232	1.00E+01	6.56E-08	2.60E-14	9.81E-03	3.89E-09
U-234	3.50E+01	8.00E-08	3.10E-14	4.19E-02	1.62E-08
U-238	3.50E+01	6.41E-08	2.50E-14	3.36E-02	1.31E-08
U-235	1.80E+00	1.67E-05	6.50E-12	4.50E-01	1.75E-07
TOTAL				1.52E+02	5.90E-05

W1h

WORKER - DIRECT GAMMA EXPOSURE
for: Oil & Gas Scale/ Sludge

$$G = 1.10E-01$$

$$S = 1.20E+05$$

$$D(\text{mrem}) = G \cdot S \cdot C \cdot \text{DFG}$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot \text{RFG}$$

Nuclide	C	DFG	RFG	D	R
Po-210	1.55E+02	8.55E-10	3.30E-16	1.75E-03	6.75E-10
Pb-210	1.55E+02	2.91E-07	1.10E-13	5.95E-01	2.25E-07
Ra-226	1.55E+02	1.67E-04	6.50E-11	3.42E+02	1.33E-04
Th-228	5.50E+01	3.37E-04	1.30E-10	2.45E+02	9.44E-05
Ra-228	5.50E+01	9.04E-05	3.50E-11	6.56E+01	2.54E-05
Th-230	--	--	--	--	--
Th-232	--	--	--	--	--
U-234	--	--	--	--	--
U-238	--	--	--	--	--
U-235	--	--	--	--	--
TOTAL				6.53E+02	2.53E-04

W11

WORKER - DIRECT GAMMA EXPOSURE
for: Geothermal Waste

$$G = 1.10E-01$$

$$S = 1.30E+04$$

$$D(\text{mrem}) = G \cdot S \cdot C \cdot \text{DFG}$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot \text{RFG}$$

Nuclide	C	DFG	RFG	D	R
Po-210	1.10E+02	8.55E-10	3.30E-16	1.34E-04	5.19E-11
Pb-210	1.10E+02	2.91E-07	1.10E-13	4.58E-02	1.73E-08
Ra-226	1.60E+02	1.67E-04	6.50E-11	3.82E+01	1.49E-05
Th-228	3.00E+01	3.37E-04	1.30E-10	1.45E+01	5.58E-06
Ra-228	1.10E+02	9.04E-05	3.50E-11	1.42E+01	5.51E-06
Th-230	--	--	--	--	--
Th-232	--	--	--	--	--
U-234	--	--	--	--	--
U-238	--	--	--	--	--
U-235	--	--	--	--	--
TOTAL				6.69E+01	2.60E-05

W2a

WORKER - DUST INHALATION
for: Uranium Overburden

G= 1.68E-03

S= 1.00E+00

$D(\text{mrem}) = G \cdot S \cdot C \cdot D\text{Finh}$

$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot R\text{Finh}$

Nuclide	C	DFinh	RFinh	D	R
Po-210	1.66E+01	9.40E-03	1.50E-09	2.62E-04	4.18E-11
Pb-210	1.66E+01	1.40E-02	2.20E-09	3.90E-04	6.14E-11
Ra-226	2.37E+01	8.60E-03	1.30E-09	3.42E-04	5.18E-11
Th-228	1.00E+00	3.40E-01	5.30E-08	5.71E-04	8.90E-11
Ra-228	1.00E+00	4.80E-03	7.40E-10	8.06E-06	1.24E-12
Th-230	2.37E+01	3.30E-01	5.10E-08	1.31E-02	2.03E-09
Th-232	1.00E+00	1.60E+00	2.50E-07	2.69E-03	4.20E-10
U-234	2.37E+01	1.30E-01	2.00E-08	5.18E-03	7.96E-10
U-238	2.37E+01	1.20E-01	1.90E-08	4.78E-03	7.57E-10
U-235	1.20E+00	1.20E-01	1.90E-08	2.42E-04	3.83E-11
TOTAL				2.76E-02	4.29E-09

W2b

WORKER - DUST INHALATION
for: Phosphate Waste

G= 1.68E-03

S= 1.00E+00

$D(\text{mrem}) = G \cdot S \cdot C \cdot DF_{\text{inh}}$

$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot RF_{\text{inh}}$

Nuclide	C	DF _{inh}	RF _{inh}	D	R
Po-210	2.64E+01	9.40E-03	1.50E-09	4.17E-04	6.65E-11
Pb-210	2.84E+01	1.40E-02	2.20E-09	6.21E-04	9.76E-11
Ra-226	3.30E+01	8.60E-03	1.30E-09	4.77E-04	7.21E-11
Th-228	2.70E-01	3.40E-01	5.30E-08	1.54E-04	2.40E-11
Ra-228	2.70E-01	4.80E-03	7.40E-10	2.18E-06	3.36E-13
Th-230	1.30E+01	3.30E-01	5.10E-08	7.21E-03	1.11E-09
Th-232	2.70E-01	1.60E+00	2.50E-07	7.26E-04	1.13E-10
U-234	6.20E+00	1.30E-01	2.00E-08	1.35E-03	2.08E-10
U-238	6.00E+00	1.20E-01	1.90E-08	1.21E-03	1.92E-10
U-235	3.00E-01	1.20E-01	1.90E-08	6.05E-05	9.58E-12
TOTAL				1.22E-02	1.90E-09

W2c

WORKE 1 - DUST INHALATION
Phc :phate Fertilizer

G= 1.68E-03
S= 1.00E+00

$$D(\text{mrem}) = \cdot S \cdot C \cdot D\text{Finh}$$

$$R(\text{fatal cancr rs}) = G \cdot S \cdot C \cdot R\text{Finh}$$

Nuclide	C	DFinh	RFinh	D	R
Po-210	1.80E-03	9.40E-03	1.50E-09	2.84E-08	4.54E-15
Pb-210	1.80E-03	1.40E-02	2.20E-09	4.23E-08	6.65E-15
Ra-226	2.50E-03	8.60E-03	1.30E-09	3.61E-08	5.46E-15
Th-228	3.40E-04	3.40E-01	5.30E-08	1.94E-07	3.03E-14
Ra-228	3.40E-04	4.80E-03	7.40E-10	2.74E-09	4.23E-16
Th-230	1.60E-02	3.30E-01	5.10E-08	8.87E-06	1.37E-12
Th-232	3.10E-04	1.60E+00	2.50E-07	8.33E-07	1.30E-13
U-234	1.70E-02	1.30E-01	2.00E-08	3.71E-06	5.71E-13
U-238	1.70E-02	1.20E-01	1.90E-08	3.43E-06	5.43E-13
U-235	8.60E-04	1.20E-01	1.90E-08	1.73E-07	2.75E-14
TOTAL				1.73E-05	2.69E-12

W2d

WORKER - DUST INHALATION
for: Coal Ash

G= 1.68E-03

S= 1.00E+00

D(mrem) = G * S * C * DFinh

R(fatal cancers) = G * S * C * RFinh

Nuclide	C	DFinh	RFinh	D	R
Po-210	7.00E+00	9.40E-03	1.50E-09	1.11E-04	1.76E-11
Pb-210	6.80E+00	1.40E-02	2.20E-09	1.60E-04	2.51E-11
Ra-226	3.70E+00	8.60E-03	1.30E-09	5.35E-05	8.08E-12
Th-228	3.20E+00	3.40E-01	5.30E-08	1.83E-03	2.85E-10
Ra-228	1.80E+00	4.80E-03	7.40E-10	1.45E-05	2.24E-12
Th-230	2.30E+00	3.30E-01	5.10E-08	1.28E-03	1.97E-10
Th-232	2.10E+00	1.60E+00	2.50E-07	5.64E-03	8.82E-10
U-234	3.30E+00	1.30E-01	2.00E-08	7.21E-04	1.11E-10
U-238	3.30E+00	1.20E-01	1.90E-08	6.65E-04	1.05E-10
U-235	1.60E-01	1.20E-01	1.90E-08	3.23E-05	5.11E-12
TOTAL				1.05E-02	1.64E-09

W2a

WORKER - DUST INHALATION
for: Water Treat Sludge (Fertilizer)

G= 1.68E-03
S= 1.00E+00

D(mrem) = G * S * C * DFinh
R(fatal cancers) = G * S * C * RFinh

Nuclide	C	DFinh	RFinh	D	R
Po-210	4.00E-01	9.40E-03	1.50E-09	6.32E-06	1.01E-12
Pb-210	4.00E-01	1.40E-02	2.20E-09	9.41E-06	1.48E-12
Ra-226	6.40E-01	8.60E-03	1.30E-09	9.25E-06	1.40E-12
Th-228	8.00E-03	3.40E-01	5.30E-08	4.57E-06	7.12E-13
Ra-228	8.00E-01	4.80E-03	7.40E-10	6.45E-06	9.95E-13
Th-230	8.00E-03	3.30E-01	5.10E-08	4.44E-06	6.85E-13
Th-232	8.00E-03	1.60E+00	2.50E-07	2.15E-05	3.36E-12
U-234	1.60E-01	1.30E-01	2.00E-08	3.49E-05	5.38E-12
U-238	1.60E-01	1.20E-01	1.90E-08	3.23E-05	5.11E-12
U-235	1.20E-03	1.20E-01	1.90E-08	2.42E-07	3.83E-14
TOTAL				1.29E-04	2.02E-11

W21

WORKER - DUST INHALATION
for: Water Treat Sludge (Landfill)

G= 1.68E-03
 S= 1.00E+00

D(mrem) = G * S * C * DFinh
 R(fatal cancers) = G * S * C * RFinh

Nuclide	C	DFinh	RFinh	D	R
Po-210	1.50E-01	9.40E-03	1.50E-09	2.37E-06	3.78E-13
Pb-210	1.50E-01	1.40E-02	2.20E-09	3.53E-06	5.54E-13
Ra-226	2.40E-01	8.60E-03	1.30E-09	3.47E-06	5.24E-13
Th-228	3.00E-03	3.40E-01	5.30E-08	1.71E-06	2.67E-13
Ra-228	3.00E-01	4.80E-03	7.40E-10	2.42E-06	3.73E-13
Th-230	3.00E-03	3.30E-01	5.10E-08	1.66E-06	2.57E-13
Th-232	3.00E-03	1.60E+00	2.50E-07	8.06E-06	1.26E-12
U-234	6.00E-02	1.30E-01	2.00E-08	1.31E-05	2.02E-12
U-238	6.00E-02	1.20E-01	1.90E-08	1.21E-05	1.92E-12
U-235	5.00E-04	1.20E-01	1.90E-08	1.01E-07	1.60E-14
TOTAL				4.85E-05	7.56E-12

W2g

WORKER - DUST INHALATION
for: Mineral Processing Waste

$G = 1.68E-03$

$S = 1.00E+00$

$D(\text{mrem}) = G \cdot S \cdot C \cdot DF_{\text{inh}}$

$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot RF_{\text{inh}}$

Nuclide	C	DF _{inh}	RF _{inh}	D	R
Po-210	2.50E+01	9.40E-03	1.50E-09	3.95E-04	6.30E-11
Pb-210	2.50E+01	1.40E-02	2.20E-09	5.88E-04	9.24E-11
Ra-226	3.50E+01	8.60E-03	1.30E-09	5.06E-04	7.64E-11
Th-228	1.00E+01	3.40E-01	5.30E-08	5.71E-03	8.90E-10
Ra-228	1.00E+01	4.80E-03	7.40E-10	8.06E-05	1.24E-11
Th-230	3.50E+01	3.30E-01	5.10E-08	1.94E-02	3.00E-09
Th-232	1.00E+01	1.60E+00	2.50E-07	2.69E-02	4.20E-09
U-234	3.50E+01	1.30E-01	2.00E-08	7.64E-03	1.18E-09
U-238	3.50E+01	1.20E-01	1.90E-08	7.06E-03	1.12E-09
U-235	1.80E+00	1.20E-01	1.90E-08	3.63E-04	5.75E-11
TOTAL				6.86E-02	1.07E-08

W2h

WORKER - DUST INHALATION
for: Oil & Gas Scale/ Sludge

G= 1.68E-03

S= 1.00E+00

D(mrem) = G * S * C * DFinh

R(fatal cancers) = G * S * C * RFinh

Nuclide	C	DFinh	RFinh	D	R
Po-210	1.55E+02	9.40E-03	1.50E-09	2.45E-03	3.91E-10
Pb-210	1.55E+02	1.40E-02	2.20E-09	3.65E-03	5.73E-10
Ra-226	1.55E+02	8.60E-03	1.30E-09	2.24E-03	3.39E-10
Th-228	5.50E+01	3.40E-01	5.30E-08	3.14E-02	4.90E-09
Ra-228	5.50E+01	4.80E-03	7.40E-10	4.44E-04	6.84E-11
Th-230	..	..	..	..	..
Th-232	..	..	..	..	..
U-234	..	..	..	..	..
U-238	..	..	..	..	..
U-235	..	..	..	..	..
TOTAL				4.02E-02	6.27E-09

W2I

WORKER - DUST INHALATION
for: Geothermal Waste

G= 1.68E-03

S= 1.00E+00

$D(\text{mrem}) = G \cdot S \cdot C \cdot D\text{Finh}$

$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot R\text{Finh}$

Nuclide	C	DFinh	RFinh	D	R
Po-210	1.10E+02	9.40E-03	1.50E-09	1.74E-03	2.77E-10
Pb-210	1.10E+02	1.40E-02	2.20E-09	2.59E-03	4.07E-10
Ra-226	1.60E+02	8.60E-03	1.30E-09	2.31E-03	3.49E-10
Th-228	3.00E+01	3.40E-01	5.30E-08	1.71E-02	2.67E-09
Ra-228	1.10E+02	4.80E-03	7.40E-10	8.87E-04	1.37E-10
Th-230	--	--	--	--	--
Th-232	--	--	--	--	--
U-234	--	--	--	--	--
U-238	--	--	--	--	--
U-235	--	--	--	--	--
TOTAL				2.47E-02	3.84E-09

W3a

WORKER - INDOOR RADON INHALATION
for: Uranium Overburden

G= 4.10E-06
S= 9.17E+08
DFr= 4.90E-06

$$R(\text{fatal cancers}) = G \cdot S \cdot \text{DFr}$$

Nuclide	R
Ra-226	1.84E-02
TOTAL	1.84E-02

W3b

WORKER - INDOOR RADON INHALATION
for: Phosphate Waste

G= 4.10E-06

S= 5.91E+08

DFr= 4.90E-06

$$R(\text{fatal cancers}) = G \cdot S \cdot \text{DFr}$$

Nuclide	R
Ra-226	1.19E-02
TOTAL	1.19E-02

W3d

WORKER - INDOOR RADON INHALATION
for: Coal Ash

G= 4.10E-06
S= 6.77E+06
DFr= 4.90E-06

$$R(\text{fatal cancers}) = G \cdot S \cdot \text{DFr}$$

Nuclide	R
Ra-226	1.36E-04
TOTAL	1.36E-04

W31

WORKER - INDOOR RADON INHALATION
for: Water Treat Sludge (Landfill)

G= 4.10E-06
S= 5.85E+06
DFr= 4.90E-06

$$R(\text{fatal cancers}) = G \cdot S \cdot \text{DFr}$$

Nuclide	R
Ra-226	1.18E-04
TOTAL	1.18E-04

W3g

WORKER - INDOOR RADON INHALATION
for: Mineral Processing Waste

G= 4.10E-06
S= 1.35E+09
DFr= 4.90E-06

$$R(\text{fatal cancers}) = G \cdot S \cdot \text{DFr}$$

Nuclide	R
Ra-226	2.71E-02
TOTAL	2.71E-02

W3h

WORKER - INDOOR RADON INHALATION
for: Oil & Gas Scale/ Sludge

$$G = 4.10E-06$$

$$S = 1.06E+09$$

$$DFr = 4.90E-06$$

$$R(\text{fatal cancers}) = G \cdot S \cdot DFr$$

Nuclide	R
Ra-226	2.13E-02
TOTAL	2.13E-02

W31

WORKER - INDOOR RADON INHALATION
for: Geothermal Waste

G= 4.10E-06
S= 4.64E+09
DFr= 4.90E-06

$$R(\text{fatal cancers}) = G \cdot S \cdot \text{DFr}$$

Nuclide	R
Ra-226	9.32E-02
TOTAL	9.32E-02

11a

ONSITE INDIVIDUAL - DIRECT GAMMA EXPOSURE
for: Uranium Overburden

G= 5.00E-01

S= 1.33E+05

D(mrem) = G * S * C * DFG

R(fatal cancers) = G * S * C * RFG

Nuclide	C	DFG	RFG	D	R
Po-210	1.66E+01	8.55E-10	3.30E-16	9.44E-04	3.64E-10
Pb-210	1.66E+01	2.91E-07	1.10E-13	3.21E-01	1.21E-07
Ra-226	2.37E+01	1.67E-04	6.50E-11	2.63E+02	1.02E-04
Th-228	1.00E+00	3.37E-04	1.30E-10	2.24E+01	8.65E-06
Ra-228	1.00E+00	9.04E-05	3.50E-11	6.01E+00	2.33E-06
Th-230	2.37E+01	8.88E-08	3.50E-14	1.40E-01	5.52E-08
Th-232	1.00E+00	6.56E-08	2.60E-14	4.36E-03	1.73E-09
U-234	2.37E+01	8.00E-08	3.10E-14	1.26E-01	4.89E-08
U-238	2.37E+01	6.41E-08	2.50E-14	1.01E-01	3.94E-08
U-235	1.20E+00	1.67E-05	6.50E-12	1.33E+00	5.19E-07
TOTAL				2.94E+02	1.14E-04

11b

**ONSITE INDIVIDUAL - DIRECT GAMMA EXPOSURE
for: Phosphate Waste**

G= 5.00E-01
S= 1.59E+05

D(mrem) = G * S * C * DFG
R(fatal cancers) = G * S * C * RFG

Nuclide	C	DFG	RFG	D	R
Po-210	2.64E+01	8.55E-10	3.30E-16	1.79E-03	6.93E-10
Pb-210	2.64E+01	2.91E-07	1.10E-13	6.11E-01	2.31E-07
Ra-226	3.30E+01	1.67E-04	6.50E-11	4.38E+02	1.71E-04
Th-228	2.70E-01	3.37E-04	1.30E-10	7.23E+00	2.79E-06
Ra-228	2.70E-01	9.04E-05	3.50E-11	1.94E+00	7.51E-07
Th-230	1.30E+01	8.88E-08	3.50E-14	9.18E-02	3.62E-08
Th-232	2.70E-01	6.56E-08	2.60E-14	1.41E-03	5.58E-10
U-234	6.20E+00	8.00E-08	3.10E-14	3.94E-02	1.53E-08
U-238	6.00E+00	6.41E-08	2.50E-14	3.06E-02	1.19E-08
U-235	3.00E-01	1.67E-05	6.50E-12	3.98E-01	1.55E-07
TOTAL				4.48E+02	1.75E-04

11e

ONSITE INDIVIDUAL - DIRECT GAMMA EXPOSURE
Phosphate Fertilizer

G= 5.00E-01

S= 9.66E+04

D(mrem) = G * S * C * DFG

R(fatal cancers) = G * S * C * RFG

Nuclide	C	DFG	RFG	D	R
Po-210	1.80E-03	8.55E-10	3.30E-16	7.43E-08	2.87E-14
Pb-210	1.80E-03	2.91E-07	1.10E-13	2.53E-05	9.56E-12
Ra-226	2.50E-03	1.67E-04	6.50E-11	2.02E-02	7.85E-09
Th-228	3.40E-04	3.37E-04	1.30E-10	5.53E-03	2.13E-09
Ra-228	3.40E-04	9.04E-05	3.50E-11	1.48E-03	5.75E-10
Th-230	1.60E-02	8.88E-08	3.50E-14	6.86E-05	2.70E-11
Th-232	3.10E-04	6.56E-08	2.60E-14	9.82E-07	3.89E-13
U-234	1.70E-02	8.00E-08	3.10E-14	6.57E-05	2.55E-11
U-238	1.70E-02	6.41E-08	2.50E-14	5.26E-05	2.05E-11
U-235	8.60E-04	1.67E-05	6.50E-12	6.94E-04	2.70E-10
TOTAL				2.81E-02	1.09E-08

ONSITE INDIVIDUAL - DIRECT GAMMA EXPOSURE
for: Coal Ash

G= 5.00E-01

S= 7.98E+04

D(mrem) = G * S * C * DFG

R(fatal cancers) = G * S * C * RFG

Nuclide	C	DFG	RFG	D	R
Po-210	7.00E+00	8.55E-10	3.30E-16	2.39E-04	9.22E-11
Pb-210	6.80E+00	2.91E-07	1.10E-13	7.90E-02	2.98E-08
Ra-226	3.70E+00	1.67E-04	6.50E-11	2.47E+01	9.60E-06
Th-228	3.20E+00	3.37E-04	1.30E-10	4.30E+01	1.66E-05
Ra-228	1.80E+00	9.04E-05	3.50E-11	6.49E+00	2.51E-06
Th-230	2.30E+00	8.88E-08	3.50E-14	8.15E-03	3.21E-09
Th-232	2.10E+00	6.56E-08	2.60E-14	5.50E-03	2.18E-09
U-234	3.30E+00	8.00E-08	3.10E-14	1.05E-02	4.08E-09
U-238	3.30E+00	6.41E-08	2.50E-14	8.44E-03	3.29E-09
U-235	1.60E-01	1.67E-05	6.50E-12	1.07E-01	4.15E-08
TOTAL				7.44E+01	2.88E-05

11e

ONSITE INDIVIDUAL - DIRECT GAMMA EXPOSURE
for: Water Treat Sludge (Fertilizer)

G= 5.00E-01
S= 1.13E+05

D(mrem) = G * S * C * DFG
R(fatal cancers) = G * S * C * RFG

Nuclide	C	DFG	RFG	D	R
Po-210	4.00E-01	8.55E-10	3.30E-16	1.93E-05	7.46E-12
Pb-210	4.00E-01	2.91E-07	1.10E-13	6.58E-03	2.49E-09
Ra-226	6.40E-01	1.67E-04	6.50E-11	6.04E+00	2.35E-06
Th-228	8.00E-03	3.37E-04	1.30E-10	1.52E-01	5.88E-08
Ra-228	8.00E-01	9.04E-05	3.50E-11	4.09E+00	1.58E-06
Th-230	8.00E-03	8.88E-08	3.50E-14	4.01E-05	1.58E-11
Th-232	8.00E-03	6.56E-08	2.60E-14	2.97E-05	1.18E-11
U-234	1.60E-01	8.00E-08	3.10E-14	7.23E-04	2.80E-10
U-238	1.60E-01	6.41E-08	2.50E-14	5.79E-04	2.26E-10
U-235	1.20E-03	1.67E-05	6.50E-12	1.13E-03	4.41E-10
TOTAL				1.03E+01	3.99E-06

**ONSITE INDIVIDUAL - DIRECT GAMMA EXPOSURE
for: Water Treat Sludge (Landfill)**

$$G = 5.00E-01$$

$$S = 1.06E+05$$

$$D(\text{mrem}) = G \cdot S \cdot C \cdot \text{DFG}$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot \text{RFG}$$

Nuclide	C	DFG	RFG	D	R
Po-210	1.50E-01	8.55E-10	3.30E-16	6.80E-06	2.62E-12
Pb-210	1.50E-01	2.91E-07	1.10E-13	2.31E-03	8.75E-10
Ra-226	2.40E-01	1.67E-04	6.50E-11	2.12E+00	8.27E-07
Th-228	3.00E-03	3.37E-04	1.30E-10	5.36E-02	2.07E-08
Ra-228	3.00E-01	9.04E-05	3.50E-11	1.44E+00	5.57E-07
Th-230	3.00E-03	8.88E-08	3.50E-14	1.41E-05	5.57E-12
Th-232	3.00E-03	6.56E-08	2.60E-14	1.04E-05	4.13E-12
U-234	6.00E-02	8.00E-08	3.10E-14	2.54E-04	9.86E-11
U-238	6.00E-02	6.41E-08	2.50E-14	2.04E-04	7.95E-11
U-235	5.00E-04	1.67E-05	6.50E-12	4.43E-04	1.72E-10
TOTAL				3.62E+00	1.41E-06

ONSITE INDIVIDUAL - DIRECT GAMMA EXPOSURE
for: Mineral Processing Waste

G= 5.00E-01

S= 1.36E+05

D(mrem) = G * S * C * DFG

R(fatal cancers) = G * S * C * RFG

Nuclide	C	DFG	RFG	D	R
Po-210	2.50E+01	8.55E-10	3.30E-16	1.45E-03	5.61E-10
Pb-210	2.50E+01	2.91E-07	1.10E-13	4.95E-01	1.87E-07
Ra-226	3.50E+01	1.67E-04	6.50E-11	3.97E+02	1.55E-04
Th-228	1.00E+01	3.37E-04	1.30E-10	2.29E+02	8.84E-05
Ra-228	1.00E+01	9.04E-05	3.50E-11	6.15E+01	2.38E-05
Th-230	3.50E+01	8.88E-08	3.50E-14	2.11E-01	8.33E-08
Th-232	1.00E+01	6.56E-08	2.60E-14	4.46E-02	1.77E-08
U-234	3.50E+01	8.00E-08	3.10E-14	1.90E-01	7.38E-08
U-238	3.50E+01	6.41E-08	2.50E-14	1.53E-01	5.95E-08
U-235	1.80E+00	1.67E-05	6.50E-12	2.04E+00	7.96E-07
			TOTAL	6.91E+02	2.68E-04

11h

**ONSITE INDIVIDUAL - DIRECT GAMMA EXPOSURE
for: Oil & Gas Scale/ Sludge**

G= 5.00E-01

S= 1.20E+05

D(mrem) = G * S * C * DFG

R(fatal cancers) = G * S * C * RFG

Nuclide	C	DFG	RFG	D	R
Po-210	1.55E+02	8.55E-10	3.30E-16	7.95E-03	3.07E-09
Pb-210	1.55E+02	2.91E-07	1.10E-13	2.71E+00	1.02E-06
Ra-226	1.55E+02	1.67E-04	6.50E-11	1.55E+03	6.05E-04
Th-228	5.50E+01	3.37E-04	1.30E-10	1.11E+03	4.29E-04
Ra-228	5.50E+01	9.04E-05	3.50E-11	2.98E+02	1.16E-04
Th-230	--	--	--	--	--
Th-232	--	--	--	--	--
U-234	--	--	--	--	--
U-238	--	--	--	--	--
U-235	--	--	--	--	--
TOTAL				2.97E+03	1.15E-03

ONSITE INDIVIDUAL - DIRECT GAMMA EXPOSURE
for: Geothermal Waste

G= 5.00E-01

S= 1.30E+04

D(mrem) = G * S * C * DFG

R(fatal cancers) = G * S * C * RFG

Nuclide	C	DFG	RFG	D	R
Po-210	1.10E+02	8.55E-10	3.30E-16	6.11E-04	2.36E-10
Pb-210	1.10E+02	2.91E-07	1.10E-13	2.08E-01	7.87E-08
Ra-226	1.60E+02	1.67E-04	6.50E-11	1.74E+02	6.76E-05
Th-228	3.00E+01	3.37E-04	1.30E-10	6.57E+01	2.54E-05
Ra-228	1.10E+02	9.04E-05	3.50E-11	6.46E+01	2.50E-05
Th-230	--	--	--	--	--
Th-232	--	--	--	--	--
U-234	--	--	--	--	--
U-238	--	--	--	--	--
U-235	--	--	--	--	--
TOTAL				3.04E+02	1.18E-04

12a

ONST : INDIVIDUAL - INDOOR RADON INHALATION
for: Uranium Overburden

G= .34E-05
S= .17E+08
DFr= .90E-06

$$R(\text{fatal cancer}) = G \cdot S \cdot \text{DFr}$$

Nuclide	R
Ra-226	6.02E-02
TOTAL	6.02E-02

12b

ONSITE INDIVIDUAL - INDOOR RADON INHALATION
for: Phosphate Waste

G= 1.34E-05
S= 5.91E+08
DFr= 4.90E-06

$$R(\text{fatal cancers}) = G \cdot S \cdot \text{DFr}$$

Nuclide	R
Ra-226	3.88E-02
TOTAL	3.88E-02

12c

ONSITE INDIVIDUAL - INDOOR RADON INHALATION
for: Phosphate Fertilizer

G= 1.34E-05
S= 4.57E+04
DFr= 4.90E-06

$$R(\text{fatal cancers}) = G \cdot S \cdot \text{DFr}$$

Nuclide	R
Ra-226	3.00E-06
TOTAL	3.00E-06

12d

ONSITE INDIVIDUAL - INDOOR RADON INHALATION
for: Coal Ash

G= 1.34E-05
S= 6.77E+06
DFr= 4.90E-06

$$R(\text{fatal cancers}) = G \cdot S \cdot \text{DFr}$$

Nuclide	R
Ra-226	4.45E-04
TOTAL	4.45E-04

12e

ONSITE INDIVIDUAL - INDOOR RADON INHALATION
for: Water Treat Sludge (Fertilizer)

G= 1.34E-05
S= 1.56E+07
DFr= 4.90E-06

$$R(\text{fatal cancers}) = G \cdot S \cdot DFr$$

Nuclide	R
Ra-226	1.02E-03
TOTAL	1.02E-03

121

ONSITE INDIVIDUAL - INDOOR RADON INHALATION
for: Water Treat Sludge (Landfill)

G= 1.34E-05
S= 5.85E+06
Dfr= 4.90E-06

$$R(\text{fatal cancers}) = G \cdot S \cdot DFr$$

Nuclide	R
Ra-226	3.84E-04
TOTAL	3.84E-04

12g

ONSITE INDIVIDUAL - INDOOR RADON INHALATION
for: Mineral Processing Waste

G= 1.34E-05
S= 1.35E+09
DFr= 4.90E-06

$$R(\text{fatal cancers}) = G \cdot S \cdot \text{DFr}$$

Nuclide	R
Ra-226	8.86E-02
TOTAL	8.86E-02

12h

ONSITE INDIVIDUAL - INDOOR RADON INHALATION
for: Oil & Gas Scale/ Sludge

G= 1.34E-06
S= 1.06E+09
DFr= 4.90E-06

$$R(\text{fatal cancers}) = G \cdot S \cdot \text{DFr}$$

Nuclide	R
Ra-226	6.96E-02
TOTAL	6.96E-02

121

ONSITE INDIVIDUAL - INDOOR RADON INHALATION
for: Geothermal Waste

G= 1.34E-05

S= 4.64E+09

Dfr= 4.90E-06

$$R(\text{fatal cancers}) = G \cdot S \cdot DFr$$

Nuclide	R
Ra-226	3.05E-01
TOTAL	3.05E-01

13e

AVERAGE CPQ - DIRECT GAMMA EXPOSURE
for: Uranium Overburden

$$G = 1.52E-01$$

$$S = 1.33E+05$$

$$D(\text{mrem}) = G \cdot S \cdot C \cdot \text{DFG}$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot \text{RFG}$$

Nuclide	C	DFG	RFG	D	R
Po-210	1.66E+01	8.55E-10	3.30E-16	2.87E-04	1.11E-10
Pb-210	1.66E+01	2.91E-07	1.10E-13	9.77E-02	3.69E-08
Ra-226	2.37E+01	1.67E-04	6.50E-11	8.00E+01	3.11E-05
Th-228	1.00E+00	3.37E-04	1.30E-10	6.81E+00	2.63E-06
Ra-228	1.00E+00	9.04E-05	3.50E-11	1.83E+00	7.08E-07
Th-230	2.37E+01	8.88E-08	3.50E-14	4.25E-02	1.68E-08
Th-232	1.00E+00	6.56E-08	2.60E-14	1.33E-03	5.26E-10
U-234	2.37E+01	8.00E-08	3.10E-14	3.83E-02	1.49E-08
U-238	2.37E+01	6.41E-08	2.50E-14	3.07E-02	1.20E-08
U-235	1.20E+00	1.67E-05	6.50E-12	4.05E-01	1.58E-07
TOTAL				8.93E+01	3.47E-05

13b

**AVERAGE CPG - DIRECT GAMMA EXPOSURE
for: Phosphate Waste**

$$G = 1.52E-01$$

$$S = 1.59E+05$$

$$D(\text{mrem}) = G \cdot S \cdot C \cdot \text{DFG}$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot \text{RFG}$$

Nuclide	C	DFG	RFG	D	R
Po-210	2.64E+01	8.55E-10	3.30E-16	5.46E-04	2.11E-10
Pb-210	2.64E+01	2.91E-07	1.10E-13	1.86E-01	7.02E-08
Ra-226	3.30E+01	1.67E-04	6.50E-11	1.33E+02	5.18E-05
Th-228	2.70E-01	3.37E-04	1.30E-10	2.20E+00	8.48E-07
Ra-228	2.70E-01	9.04E-05	3.50E-11	5.90E-01	2.28E-07
Th-230	1.30E+01	8.88E-08	3.50E-14	2.79E-02	1.10E-08
Th-232	2.70E-01	6.56E-08	2.60E-14	4.28E-04	1.70E-10
U-234	6.20E+00	8.00E-08	3.10E-14	1.20E-02	4.65E-09
U-238	6.00E+00	6.41E-08	2.50E-14	9.30E-03	3.63E-09
U-235	3.00E-01	1.67E-05	6.50E-12	1.21E-01	4.71E-08
TOTAL				1.36E+02	5.31E-05

13c

AVERAGE CPG - DIRECT GAMMA EXPOSURE
Phosphate Fertilizer

G= 1.52E-01
S= 9.66E+04

D(mrem) = G * S * C * DFG
R(fatal cancers) = G * S * C * RFG

Nuclide	C	DFG	RFG	D	R
Po-210	1.80E-03	8.55E-10	3.30E-16	2.26E-08	8.72E-15
Pb-210	1.80E-03	2.91E-07	1.10E-13	7.69E-06	2.91E-12
Ra-226	2.50E-03	1.67E-04	6.50E-11	6.13E-03	2.39E-09
Th-228	3.40E-04	3.37E-04	1.30E-10	1.68E-03	6.49E-10
Ra-228	3.40E-04	9.04E-05	3.50E-11	4.51E-04	1.75E-10
Th-230	1.60E-02	8.88E-08	3.50E-14	2.09E-05	8.22E-12
Th-232	3.10E-04	6.56E-08	2.60E-14	2.99E-07	1.18E-13
U-234	1.70E-02	8.00E-08	3.10E-14	2.00E-05	7.74E-12
U-238	1.70E-02	6.41E-08	2.50E-14	1.60E-05	6.24E-12
U-235	8.60E-04	1.67E-05	6.50E-12	2.11E-04	8.21E-11
TOTAL				8.54E-03	3.32E-09

13d

AVERAGE CPG - DIRECT GAMMA EXPOSURE
for: Coal Ash

$$G = 1.52E-01$$

$$S = 7.98E+04$$

$$D(\text{mrem}) = G \cdot S \cdot C \cdot \text{DFG}$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot \text{RFG}$$

Nuclide	C	DFG	RFG	D	R
Po-210	7.00E+00	8.55E-10	3.30E-16	7.26E-05	2.80E-11
Pb-210	6.80E+00	2.91E-07	1.10E-13	2.40E-02	9.07E-09
Ra-226	3.70E+00	1.67E-04	6.50E-11	7.49E+00	2.92E-06
Th-228	3.20E+00	3.37E-04	1.30E-10	1.31E+01	5.05E-06
Ra-228	1.80E+00	9.04E-05	3.50E-11	1.97E+00	7.64E-07
Th-230	2.30E+00	8.88E-08	3.50E-14	2.48E-03	9.76E-10
Th-232	2.10E+00	6.56E-08	2.60E-14	1.67E-03	6.62E-10
U-234	3.30E+00	8.00E-08	3.10E-14	3.20E-03	1.24E-09
U-238	3.30E+00	6.41E-08	2.50E-14	2.57E-03	1.00E-09
U-235	1.80E-01	1.87E-05	6.50E-12	3.24E-02	1.26E-08
TOTAL				2.26E+01	8.75E-06

13●

**AVERAGE CPG - DIRECT GAMMA EXPOSURE
for: Water Treat Sludge (Fertilizer)**

$$G = 1.52E-01$$

$$S = 1.13E+05$$

$$D(\text{mrem}) = G \cdot S \cdot C \cdot \text{DFG}$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot \text{RFG}$$

Nuclide	C	DFG	RFG	D	R
Po-210	4.00E-01	8.55E-10	3.30E-16	5.87E-06	2.27E-12
Pb-210	4.00E-01	2.91E-07	1.10E-13	2.00E-03	7.56E-10
Ra-226	6.40E-01	1.67E-04	6.50E-11	1.84E+00	7.15E-07
Th-228	8.00E-03	3.37E-04	1.30E-10	4.63E-02	1.79E-08
Ra-228	8.00E-01	9.04E-05	3.50E-11	1.24E+00	4.81E-07
Th-230	8.00E-03	8.88E-08	3.50E-14	1.22E-05	4.81E-12
Th-232	8.00E-03	6.56E-08	2.60E-14	9.01E-06	3.57E-12
U-234	1.60E-01	8.00E-08	3.10E-14	2.20E-04	8.52E-11
U-238	1.60E-01	6.41E-08	2.50E-14	1.76E-04	6.87E-11
U-235	1.20E-03	1.67E-05	6.50E-12	3.44E-04	1.34E-10
TOTAL				3.13E+00	1.21E-06

AVERAGE CPG - DIRECT GAMMA EXPOSURE
for: Water Treat Sludge (Landfill)

$$G = 1.52E-01$$

$$S = 1.06E+05$$

$$D(\text{mrem}) = G \cdot S \cdot C \cdot \text{DFG}$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot \text{RFG}$$

Nuclide	C	DFG	RFG	D	R
Po-210	1.50E-01	8.55E-10	3.30E-16	2.07E-06	7.98E-13
Pb-210	1.50E-01	2.91E-07	1.10E-13	7.03E-04	2.66E-10
Ra-226	2.40E-01	1.67E-04	6.50E-11	6.46E-01	2.51E-07
Th-228	3.00E-03	3.37E-04	1.30E-10	1.63E-02	6.28E-09
Ra-228	3.00E-01	9.04E-05	3.50E-11	4.37E-01	1.69E-07
Th-230	3.00E-03	8.88E-08	3.50E-14	4.29E-06	1.69E-12
Th-232	3.00E-03	6.56E-08	2.60E-14	3.17E-06	1.26E-12
U-234	6.00E-02	8.00E-08	3.10E-14	7.73E-05	3.00E-11
U-238	6.00E-02	6.41E-08	2.50E-14	6.20E-05	2.42E-11
U-235	5.00E-04	1.67E-05	6.50E-12	1.35E-04	5.24E-11
TOTAL				1.10E+00	4.27E-07

13g

**AVERAGE CPG - DIRECT GAMMA EXPOSURE
for: Mineral Processing Waste**

G= 1.52E-01

S= 1.36E+05

D(mrem) = G * S * C * DFG

R(fatal cancers) = G * S * C * RFG

Nuclide	C	DFG	RFG	D	R
Po-210	2.50E+01	8.55E-10	3.30E-16	4.42E-04	1.71E-10
Pb-210	2.50E+01	2.91E-07	1.10E-13	1.50E-01	5.68E-08
Ra-226	3.50E+01	1.67E-04	6.50E-11	1.21E+02	4.70E-05
Th-228	1.00E+01	3.37E-04	1.30E-10	6.97E+01	2.69E-05
Ra-228	1.00E+01	9.04E-05	3.50E-11	1.87E+01	7.24E-06
Th-230	3.50E+01	8.88E-08	3.50E-14	6.42E-02	2.53E-08
Th-232	1.00E+01	6.56E-08	2.60E-14	1.36E-02	5.37E-09
U-234	3.50E+01	8.00E-08	3.10E-14	5.79E-02	2.24E-08
U-238	3.50E+01	6.41E-08	2.50E-14	4.64E-02	1.81E-08
U-235	1.80E+00	1.67E-05	6.50E-12	6.21E-01	2.42E-07
TOTAL				2.10E+02	8.15E-05

13h

AVERAGE CPG - DIRECT GAMMA EXPOSURE
for: Oil & Gas Scale/ Sludge

$$G = 1.52E-01$$

$$S = 1.20E+05$$

$$D(\text{mrem}) = G \cdot S \cdot C \cdot \text{DFG}$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot \text{RFG}$$

Nuclide	C	DFG	RFG	D	R
Po-210	1.55E+02	8.55E-10	3.30E-16	2.42E-03	9.33E-10
Pb-210	1.55E+02	2.91E-07	1.10E-13	8.23E-01	3.11E-07
Ra-226	1.55E+02	1.67E-04	6.50E-11	4.72E+02	1.84E-04
Th-228	5.50E+01	3.37E-04	1.30E-10	3.38E+02	1.30E-04
Ra-228	5.50E+01	9.04E-05	3.50E-11	9.07E+01	3.51E-05
Th-230	--	--	--	--	--
Th-232	--	--	--	--	--
U-234	--	--	--	--	--
U-238	--	--	--	--	--
U-235	--	--	--	--	--
TOTAL				9.02E+02	3.50E-04

AVERAGE CPG - DIRECT GAMMA EXPOSURE
for: Geothermal Waste

$$G = 1.52E-01$$

$$S = 1.30E+04$$

$$D(\text{mrem}) = G \cdot S \cdot C \cdot \text{DFG}$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot \text{RFG}$$

Nuclide	C	DFG	RFG	D	R
Po-210	1.10E+02	8.55E-10	3.30E-16	1.86E-04	7.17E-11
Pb-210	1.10E+02	2.91E-07	1.10E-13	6.33E-02	2.39E-08
Ra-226	1.60E+02	1.67E-04	6.50E-11	5.28E+01	2.06E-05
Th-228	3.00E+01	3.37E-04	1.30E-10	2.00E+01	7.71E-06
Ra-228	1.10E+02	9.04E-05	3.50E-11	1.96E+01	7.61E-06
Th-230	--	--	--	--	--
Th-232	--	--	--	--	--
U-234	--	--	--	--	--
U-238	--	--	--	--	--
U-235	--	--	--	--	--
TOTAL				9.25E+01	3.59E-05

AVERAGE CPG - INHALATION OF CONTAMINATED DUST
for: Uranium Overburden

$$G = 2.36E+03$$

$$S = 6.90E-07$$

$$D(\text{mrem}) = G \cdot S \cdot C \cdot D\text{Finh}$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot R\text{Finh}$$

Nuclide	C	DFinh	RFinh	D	R
Po-210	1.66E+01	9.40E-03	1.50E-09	2.54E-04	4.05E-11
Pb-210	1.66E+01	1.40E-02	2.20E-09	3.78E-04	5.95E-11
Ra-226	2.37E+01	8.60E-03	1.30E-09	3.32E-04	5.02E-11
Th-228	1.00E+00	3.40E-01	5.30E-08	5.54E-04	8.63E-11
Ra-228	1.00E+00	4.80E-03	7.40E-10	7.82E-06	1.21E-12
Th-230	2.37E+01	3.30E-01	5.10E-08	1.27E-02	1.97E-09
Th-232	1.00E+00	1.60E+00	2.50E-07	2.61E-03	4.07E-10
U-234	2.37E+01	1.30E-01	2.00E-08	5.02E-03	7.72E-10
U-238	2.37E+01	1.20E-01	1.90E-08	4.63E-03	7.33E-10
U-235	1.20E+00	1.20E-01	1.90E-08	2.34E-04	3.71E-11
TOTAL				2.67E-02	4.16E-09

14b

**AVERAGE CPG - INHALATION OF CONTAMINATED DUST
for: Phosphate Waste**

G= 2.36E+03

S= 2.83E-07

D(mrem) = G * S * C * DFinh

R(fatal cancers) = G * S * C * RFinh

Nuclide	C	DFinh	RFinh	D	R
Po-210	2.64E+01	9.40E-03	1.50E-09	1.66E-04	2.64E-11
Pb-210	2.64E+01	1.40E-02	2.20E-09	2.47E-04	3.88E-11
Ra-226	3.30E+01	8.60E-03	1.30E-09	1.90E-04	2.87E-11
Th-228	2.70E-01	3.40E-01	5.30E-08	6.13E-05	9.56E-12
Ra-228	2.70E-01	4.80E-03	7.40E-10	8.66E-07	1.33E-13
Th-230	1.30E+01	3.30E-01	5.10E-08	2.87E-03	4.43E-10
Th-232	2.70E-01	1.60E+00	2.50E-07	2.89E-04	4.51E-11
U-234	6.20E+00	1.30E-01	2.00E-08	5.38E-04	8.28E-11
U-238	6.00E+00	1.20E-01	1.90E-08	4.81E-04	7.61E-11
U-235	3.00E-01	1.20E-01	1.90E-08	2.40E-05	3.81E-12
TOTAL				4.86E-03	7.54E-10

14c

AVERAGE CPG - INHALATION OF CONTAMINATED DUST
Phosphate Fertilizer

G= 2.36E+03

S= 6.90E-07

D(mrem) = G * S * C * DFinh

R(fatal cancers) = G * S * C * RFinh

Nuclide	C	DFinh	RFinh	D	R
Po-210	1.80E-03	9.40E-03	1.50E-09	2.76E-08	4.40E-15
Pb-210	1.80E-03	1.40E-02	2.20E-09	4.10E-08	6.46E-15
Ra-226	2.50E-03	8.60E-03	1.30E-09	3.50E-08	5.29E-15
Th-228	3.40E-04	3.40E-01	5.30E-08	1.88E-07	2.93E-14
Ra-228	3.40E-04	4.80E-03	7.40E-10	2.66E-09	4.10E-16
Th-230	1.60E-02	3.30E-01	5.10E-08	8.60E-06	1.33E-12
Th-232	3.10E-04	1.60E+00	2.50E-07	8.08E-07	1.26E-13
U-234	1.70E-02	1.30E-01	2.00E-08	3.60E-06	5.54E-13
U-238	1.70E-02	1.20E-01	1.90E-08	3.32E-06	5.26E-13
U-235	8.60E-04	1.20E-01	1.90E-08	1.68E-07	2.66E-14
			TOTAL	1.68E-05	2.61E-12

14d

AVERAGE CPG - INHALATION OF CONTAMINATED DUST
for: Coal Ash

G= 2.36E+03

S= 1.32E-07

D(mrem) = G * S * C * DFinh

R(fatal cancers) = G * S * C * RFinh

Nuclide	C	DFinh	RFinh	D	R
Po-210	7.00E+00	9.40E-03	1.50E-09	2.05E-05	3.27E-12
Pb-210	6.80E+00	1.40E-02	2.20E-09	2.97E-05	4.66E-12
Ra-226	3.70E+00	8.60E-03	1.30E-09	9.91E-06	1.50E-12
Th-228	3.20E+00	3.40E-01	5.30E-08	3.39E-04	5.28E-11
Ra-228	1.80E+00	4.80E-03	7.40E-10	2.69E-06	4.15E-13
Th-230	2.30E+00	3.30E-01	5.10E-08	2.36E-04	3.65E-11
Th-232	2.10E+00	1.60E+00	2.50E-07	1.05E-03	1.64E-10
U-234	3.30E+00	1.30E-01	2.00E-08	1.34E-04	2.06E-11
U-238	3.30E+00	1.20E-01	1.90E-08	1.23E-04	1.95E-11
U-235	1.60E-01	1.20E-01	1.90E-08	5.98E-06	9.47E-13
TOTAL				1.95E-03	3.04E-10

**AVERAGE CPG - INHALATION OF CONTAMINATED DUST
for: Water Treat Sludge (Fertilizer)**

$$G = 2.36E+03$$

$$S = 8.28E-07$$

$$D(\text{mrem}) = G \cdot S \cdot C \cdot D\text{Finh}$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot R\text{Finh}$$

Nuclide	C	DFinh	RFinh	D	R
Po-210	4.00E-01	9.40E-03	1.50E-09	7.35E-06	1.17E-12
Pb-210	4.00E-01	1.40E-02	2.20E-09	1.09E-05	1.72E-12
Ra-226	6.40E-01	8.80E-03	1.30E-09	1.08E-05	1.63E-12
Th-228	8.00E-03	3.40E-01	5.30E-08	5.32E-06	8.29E-13
Ra-228	8.00E-01	4.80E-03	7.40E-10	7.50E-06	1.16E-12
Th-230	8.00E-03	3.30E-01	5.10E-08	5.16E-06	7.97E-13
Th-232	8.00E-03	1.60E+00	2.50E-07	2.50E-05	3.91E-12
U-234	1.60E-01	1.30E-01	2.00E-08	4.06E-05	6.25E-12
U-238	1.60E-01	1.20E-01	1.90E-08	3.75E-05	5.94E-12
U-235	1.20E-03	1.20E-01	1.90E-08	2.81E-07	4.46E-14
TOTAL				1.50E-04	2.34E-11

**AVERAGE CPQ - INHALATION OF CONTAMINATED DUST
for: Water Treat Sludge (Landfill)**

$$G = 2.36E+03$$

$$S = 8.95E-07$$

$$D(\text{mrem}) = G \cdot S \cdot C \cdot D\text{Finh}$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot R\text{Finh}$$

Nuclide	C	DFinh	RFinh	D	R
Po-210	1.50E-01	9.40E-03	1.50E-09	2.98E-01	4.75E-13
Pb-210	1.50E-01	1.40E-02	2.20E-09	4.44E-01	6.97E-13
Ra-226	2.40E-01	8.60E-03	1.30E-09	4.36E-01	6.59E-13
Th-228	3.00E-03	3.40E-01	5.30E-08	2.15E-01	3.36E-13
Ra-228	3.00E-01	4.80E-03	7.40E-10	3.04E-01	4.69E-13
Th-230	3.00E-03	3.30E-01	5.10E-08	2.09E-01	3.23E-13
Th-232	3.00E-03	1.60E+00	2.50E-07	1.01E-01	1.58E-12
U-234	6.00E-02	1.30E-01	2.00E-08	1.65E-01	2.53E-12
U-238	6.00E-02	1.20E-01	1.90E-08	1.52E-01	2.41E-12
U-235	5.00E-04	1.20E-01	1.90E-08	1.27E-01	2.01E-14
TOTAL				6.10E-01	9.51E-12

14g

**AVERAGE CPG - INHALATION OF CONTAMINATED DUST
for: Mineral Processing Waste**

$$G = 2.36E+03$$

$$S = 6.85E-07$$

$$D(\text{mrem}) = G \cdot S \cdot C \cdot D\text{Finh}$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot R\text{Finh}$$

Nuclide	C	DFinh	RFinh	D	R
Po-210	2.50E+01	9.40E-03	1.50E-09	3.80E-04	6.06E-11
Pb-210	2.50E+01	1.40E-02	2.20E-09	5.66E-04	8.89E-11
Ra-226	3.50E+01	8.60E-03	1.30E-09	4.87E-04	7.36E-11
Th-228	1.00E+01	3.40E-01	5.30E-08	5.50E-03	8.57E-10
Ra-228	1.00E+01	4.80E-03	7.40E-10	7.76E-05	1.20E-11
Th-230	3.50E+01	3.30E-01	5.10E-08	1.87E-02	2.89E-09
Th-232	1.00E+01	1.60E+00	2.50E-07	2.59E-02	4.04E-09
U-234	3.50E+01	1.30E-01	2.00E-08	7.36E-03	1.13E-09
U-238	3.50E+01	1.20E-01	1.90E-08	6.79E-03	1.08E-09
U-235	1.80E+00	1.20E-01	1.90E-08	3.49E-04	5.53E-11
TOTAL				6.60E-02	1.03E-08

14h

AVERAGE CPG - INHALATION OF CONTAMINATED DUST
for: Oil & Gas Scale/ Sludge

G= 2.36E+03
S= 6.39E-08

D(mrem) = G * S * C * DFinh
R(fatal cancers) = G * S * C * RFinh

Nuclide	C	DFinh	RFinh	D	R
Po-210	1.55E+02	9.40E-03	1.50E-09	2.20E-04	3.51E-11
Pb-210	1.55E+02	1.40E-02	2.20E-09	3.27E-04	5.14E-11
Ra-226	1.55E+02	8.60E-03	1.30E-09	2.01E-04	3.04E-11
Th-228	5.50E+01	3.40E-01	5.30E-08	2.82E-03	4.40E-10
Ra-228	5.50E+01	4.80E-03	7.40E-10	3.98E-05	6.14E-12
Th-230	--	--	--	--	--
Th-232	--	--	--	--	--
U-234	--	--	--	--	--
U-238	--	--	--	--	--
U-235	--	--	--	--	--
TOTAL				3.61E-03	5.63E-10

AVERAGE CPG - INHALATION OF CONTAMINATED DUST
for: Geothermal Waste

$$G = 2.36E+03$$

$$S = 6.01E-08$$

$$D(\text{mrem}) = G \cdot S \cdot C \cdot D\text{Finh}$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot R\text{Finh}$$

Nuclide	C	DFinh	RFinh	D	R
Po-210	1.10E+02	9.40E-03	1.50E-09	1.47E-04	2.34E-11
Pb-210	1.10E+02	1.40E-02	2.20E-09	2.18E-04	3.43E-11
Ra-226	1.60E+02	8.60E-03	1.30E-09	1.95E-04	2.95E-11
Th-228	3.00E+01	3.40E-01	5.30E-08	1.45E-03	2.26E-10
Ra-228	1.10E+02	4.80E-03	7.40E-10	7.49E-05	1.15E-11
Th-230	--	--	--	--	--
Th-232	--	--	--	--	--
U-234	--	--	--	--	--
U-238	--	--	--	--	--
U-235	--	--	--	--	--
TOTAL				2.08E-03	3.24E-10

15a

AVERAGE CPG-DOWNWIND EXPOSURE TO RADON
for: Uranium Overburden

G= 2.95E-01
S= 2.97E+00
DFr= 4.90E-07

$$R(\text{fatal cancers}) = G \cdot S \cdot \text{DFr}$$

Nuclide	R
Ra-226	4.29E-07
TOTAL	4.29E-07

15b

**AVERAGE CPG-DOWNWIND EXPOSURE TO RADON
for: Phosphate Waste**

**G= 2.95E-01
S= 1.96E+00
DFr= 4.90E-07**

$$R(\text{fatal cancers}) = G \cdot S \cdot DFr$$

Nuclide	R
Ra-226	2.83E-07
TOTAL	2.83E-07

15c

**AVERAGE CPG -DOWNWIND EXPOSURE TO RA/ ON
for: *Phosphate Fertilizer***

G= 2.95E-01

S= 3.76E-05

Dfr= 4.90E-07

$$R(\text{fatal cancers}) = G \cdot S \cdot DFr$$

Nuclide	R
Ra-226	5.44E-12
TOTAL	5.44E-12

15d

**AVERAGE CPG -DOWNWIND EXPOSURE TO RADON
for: Coal Ash**

**G= 2.95E-01
S= 2.09E-02
DFr= 4.90E-07**

$$R(\text{fatal cancers}) = G \cdot S \cdot DFr$$

Nuclide	R
Ra-226	3.02E-09
TOTAL	3.02E-09

150

AVERAGE CPG -DOWNWIND EXPOSURE TO RADON
for: Water Treat Sludge (Fertilizer)

G= 2.95E-01

S= 1.10E-02

DFr= 4.90E-07

$$R(\text{fatal cancers}) = G \cdot S \cdot DFr$$

Nuclide	R
Ra-226	1.59E-09
TOTAL	1.59E-09

151

AVERAGE CPG -DOWNWIND EXPOSURE TO RADON
for: Water Treat Sludge (Landfill)

G= 2.95E-01
S= 1.76E-02
DFr= 4.90E-07

$$R(\text{fatal cancers}) = G \cdot S \cdot DFr$$

Nuclide	R
Ra-226	2.54E-09
TOTAL	2.54E-09

15g

AVERAGE CPG -DOWNWIND EXPOSURE TO RADON
for: Mineral Processing Waste

G= 2.95E-01
S= 4.35E+00
DFr= 4.90E-07

$$R(\text{fatal cancers}) = G \cdot S \cdot \text{DFr}$$

Nuclide	R
Ra-226	6.29E-07
TOTAL	6.29E-07

15h

AVERAGE CPG-DOWNWIND EXPOSURE TO RADON
for: Oil & Gas Scale/ Sludge

G= 2.95E-01
S= 3.19E+00
DFr= 4.90E-07

$$R(\text{fatal cancers}) = G \cdot S \cdot DFr$$

Nuclide	R
Ra-226	4.61E-07
TOTAL	4.61E-07

151

AVERAGE CPG -DOWNWIND EXPOSURE TO RADON
for: Geothermal Waste

G= 2.95E-01
S= 1.31E+01
DFr= 4.90E-07

$$R(\text{fatal cancers}) = G \cdot S \cdot \text{DFr}$$

Nuclide	R
Ra-226	1.89E-06
TOTAL	1.89E-06

16b

**AVERAGE CPG - EXPOSURE TO NORM IN BUILDING MATERIALS
for: Phosphate Waste**

G= 8.48E-01

S= 2.35E+06

D(mrem) = G * S * C * DFG

R(fatal cancers) = G * S * C * RFG

Nuclide	C	DFG	RFG	D	R
Po-210	2.64E+01	8.55E-10	3.30E-16	4.50E-02	1.74E-08
Pb-210	2.64E+01	2.91E-07	1.10E-13	1.53E+01	5.79E-06
Ra-226	3.30E+01	1.67E-04	6.50E-11	1.10E+04	4.27E-03
Th-228	2.70E-01	3.37E-04	1.30E-10	1.81E+02	6.99E-05
Ra-228	2.70E-01	9.04E-05	3.50E-11	4.86E+01	1.88E-05
Th-230	1.30E+01	8.88E-08	3.50E-14	2.30E+00	9.07E-07
Th-232	2.70E-01	6.56E-08	2.60E-14	3.53E-02	1.40E-08
U-234	6.20E+00	8.00E-08	3.10E-14	9.88E-01	3.83E-07
U-238	6.00E+00	6.41E-08	2.50E-14	7.66E-01	2.99E-07
U-235	3.00E-01	1.67E-05	6.50E-12	9.98E+00	3.89E-06
TOTAL				1.12E+04	4.37E-03

16d

**AVERAGE CPQ - EXPOSURE TO NORM IN BUILDING MATERIALS
for: Coal Ash**

$$G = 8.48E-01$$

$$S = 1.20E+06$$

$$D(\text{mrem}) = G \cdot S \cdot C \cdot \text{DFG}$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot \text{RFG}$$

Nuclide	C	DFG	RFG	D	R
Po-210	7.00E+00	8.55E-10	3.30E-16	6.09E-03	2.35E-09
Pb-210	6.80E+00	2.91E-07	1.10E-13	2.01E+00	7.61E-07
Ra-226	3.70E+00	1.67E-04	6.50E-11	6.29E+02	2.45E-04
Th-228	3.20E+00	3.37E-04	1.30E-10	1.10E+03	4.23E-04
Ra-228	1.80E+00	9.04E-05	3.50E-11	1.66E+02	6.41E-05
Th-230	2.30E+00	8.88E-08	3.50E-14	2.08E-01	8.19E-08
Th-232	2.10E+00	6.56E-08	2.60E-14	1.40E-01	5.56E-08
U-234	3.30E+00	8.00E-08	3.10E-14	2.69E-01	1.04E-07
U-238	3.30E+00	6.41E-08	2.50E-14	2.15E-01	8.40E-08
U-235	1.60E-01	1.67E-05	6.50E-12	2.72E+00	1.06E-06
TOTAL				1.90E+03	7.34E-04

16g

**AVERAGE CPQ - EXPOSURE TO NORM IN BUILDING MATERIALS
for: Mineral Processing Waste**

G= 8.48E-01
S= 2.00E+06

D(mrem) = G * S * C * DFG
R(fatal cancers) = G * S * C * RFG

Nuclide	C	DFG	RFG	D	R
Po-210	2.50E+01	8.55E-10	3.30E-16	3.63E-02	1.40E-08
Pb-210	2.50E+01	2.91E-07	1.10E-13	1.23E+01	4.66E-06
Ra-226	3.50E+01	1.67E-04	6.50E-11	9.91E+03	3.86E-03
Th-228	1.00E+01	3.37E-04	1.30E-10	5.72E+03	2.20E-03
Ra-228	1.00E+01	9.04E-05	3.50E-11	1.53E+03	5.94E-04
Th-230	3.50E+01	8.88E-08	3.50E-14	5.27E+00	2.08E-06
Th-232	1.00E+01	6.56E-08	2.60E-14	1.11E+00	4.41E-07
U-234	3.50E+01	8.00E-08	3.10E-14	4.75E+00	1.84E-06
U-238	3.50E+01	6.41E-08	2.50E-14	3.80E+00	1.48E-06
U-235	1.80E+00	1.67E-05	6.50E-12	5.10E+01	1.98E-05
TOTAL				1.72E+04	6.69E-03

17a

**AVERAGE CPG - INGESTION OF
DRINKING WATER FROM A CONTAMINATED WELL
for: Uranium Overburden
G= 7.40E+00
S= 4.67E+04**

$$D(\text{mrem}) = (G \cdot S \cdot C \cdot DF_{\text{ing}} \cdot (1-\exp)) / R$$

$$R(\text{fatal cancers}) = (G \cdot S \cdot C \cdot RF_{\text{ing}} \cdot (1-\exp)) / R$$

Nuclide	C	DFing	RFing	R	1-exp	D	R
Po-210	1.6 E+01	1.90E-03	2.90E-10	2.74E+02	3.40E-05	1.35E-03	2.06E-10
Pb-210	1.6 E+01	5.40E-03	8.40E-10	4.92E+02	3.40E-05	2.14E-03	3.33E-10
Ra-226	2.3 E+01	1.30E-03	2.00E-10	2.46E+02	3.40E-05	1.47E-03	2.26E-10
Th-228	1.0 E+00	4.00E-04	6.20E-11	8.18E+04	3.40E-05	5.75E-08	8.91E-15
Ra-228	1.0 E+00	1.40E-03	2.20E-10	2.46E+02	3.40E-05	6.69E-05	1.05E-11
Th-230	2.3 E+01	5.50E-04	8.50E-11	8.18E+04	3.40E-05	1.87E-06	2.89E-13
Th-232	1.0 E+00	2.70E-03	4.20E-10	8.18E+04	3.40E-05	3.88E-07	6.03E-14
U-234	2.3 E+01	2.80E-04	4.30E-11	2.46E+02	3.40E-05	3.17E-04	4.87E-11
U-238	2.3 E+01	2.50E-04	3.90E-11	2.46E+02	3.40E-05	2.83E-04	4.41E-11
U-235	1.2 E+00	2.70E-04	4.20E-11	2.46E+02	3.40E-05	1.55E-05	2.41E-12
TOTAL						5.65E-03	8.72E-10

17b

**AVERAGE CPG - INGESTION OF
DRINKING WATER FROM A CONTAMINATED WELL
for: Phosphate Waste
G= 7.40E+00
S= 7.72E+03**

$$D(\text{mrem}) = (G \cdot S \cdot C \cdot \text{DFing} \cdot (1-\text{exp})) / R$$

$$R(\text{fatal cancers}) = (G \cdot S \cdot C \cdot \text{RFing} \cdot (1-\text{exp})) / R$$

Nuclide	C	DFing	RFing	R	1-exp	D	R
Po-210	2.64E+01	1.90E-03	2.90E-10	2.73E+03	3.50E-02	3.67E-02	61E-09
Pb-210	2.64E+01	5.40E-03	8.40E-10	4.91E+03	3.50E-02	5.81E-02	03E-09
Ra-226	3.30E+01	1.30E-03	2.00E-10	2.45E+03	3.50E-02	3.50E-02	39E-09
Th-228	2.70E-01	4.00E-04	6.20E-11	8.18E+05	3.50E-02	2.64E-07	09E-14
Ra-228	2.70E-01	1.40E-03	2.20E-10	2.45E+03	3.50E-02	3.08E-04	85E-11
Th-230	1.30E+01	5.50E-04	8.50E-11	8.18E+05	3.50E-02	1.75E-05	70E-12
Th-232	2.70E-01	2.70E-03	4.20E-10	8.18E+05	3.50E-02	1.78E-06	77E-13
U-234	6.20E+00	2.80E-04	4.30E-11	2.45E+03	3.50E-02	1.42E-03	18E-10
U-238	6.00E+00	2.50E-04	3.90E-11	2.45E+03	3.50E-02	1.22E-03	91E-10
U-235	3.00E-01	2.70E-04	4.20E-11	2.45E+03	3.50E-02	6.61E-05	03E-11
TOTAL						1.33E-01	05E-08

17c

**AVERAGE CPG - INGESTION OF
DRINKING WATER FROM A CONTAMINATED WELL
Phosphate Fertilizer
G= 7.40E+00
S= 2.18E+02**

$$D(\text{mrem}) = (G \cdot S \cdot C \cdot \text{DFing} \cdot (1-\text{exp})) / R$$

$$R(\text{fatal cancers}) = (G \cdot S \cdot C \cdot \text{RFing} \cdot (1-\text{exp})) / R$$

Nuclid.	C	DFing	RFing	R	1-exp	D	R
Po-210	1.80E-03	1.90E-03	2.90E-10	2.73E+03	8.80E-03	1.78E-08	2.71E-15
Pb-210	1.80E-03	5.40E-03	8.40E-10	4.91E+03	8.80E-03	2.81E-08	4.37E-15
Ra-226	2.50E-03	1.30E-03	2.00E-10	2.45E+03	8.80E-03	1.88E-08	2.90E-15
Th-228	3.40E-04	4.00E-04	6.20E-11	8.18E+05	8.80E-03	2.36E-12	3.66E-13
Ra-228	3.40E-04	1.40E-03	2.20E-10	2.45E+03	8.80E-03	2.76E-09	4.33E-15
Th-230	1.60E-02	5.50E-04	8.50E-11	8.18E+05	8.80E-03	1.53E-10	2.36E-17
Th-232	3.10E-04	2.70E-03	4.20E-10	8.18E+05	8.80E-03	1.45E-11	2.26E-19
U-234	1.70E-02	2.80E-04	4.30E-11	2.45E+03	8.80E-03	2.76E-08	4.24E-15
U-238	1.70E-02	2.50E-04	3.90E-11	2.45E+03	8.80E-03	2.46E-08	3.84E-15
U-235	8.60E-04	2.70E-04	4.20E-11	2.45E+03	8.80E-03	1.35E-09	2.09E-16
TOTAL						1.21E-07	1.87E-14

17d

AVERAGE CPQ - INGESTION OF
DRINKING WATER FROM A CONTAMINATED WELL
for: Coal Ash
G= 7.40E+00
S= 1.07E+04

$$D(\text{mrem}) = (G \cdot S \cdot C \cdot DF_{\text{ing}} \cdot (1-\exp)) / R$$

$$R(\text{fatal cancers}) = (G \cdot S \cdot C \cdot RF_{\text{ing}} \cdot (1-\exp)) / R$$

Nuclide	C	DF _{ing}	RF _{ing}	R	1-exp	D	R
Po-210	7.00E+00	1.90E-03	2.90E-10	5.46E+02	6.70E-02	1.29E-01	1.97E-08
Pb-210	6.80E+00	5.40E-03	8.40E-10	5.46E+02	6.70E-02	3.57E-01	5.55E-08
Ra-226	3.70E+00	1.30E-03	2.00E-10	4.10E+02	6.70E-02	6.22E-02	9.57E-09
Th-228	3.20E+00	4.00E-04	6.20E-11	1.64E+04	6.70E-02	4.14E-04	6.42E-11
Ra-228	1.80E+00	1.40E-03	2.20E-10	4.10E+02	6.70E-02	3.26E-02	5.12E-09
Th-230	2.30E+00	5.50E-04	8.50E-11	1.64E+04	6.70E-02	4.09E-04	6.32E-11
Th-232	2.10E+00	2.70E-03	4.20E-10	1.64E+04	6.70E-02	1.83E-03	2.85E-10
U-234	3.30E+00	2.80E-04	4.30E-11	2.74E+02	6.70E-02	1.79E-02	2.75E-09
U-238	3.30E+00	2.50E-04	3.90E-11	2.74E+02	6.70E-02	1.60E-02	2.49E-09
U-235	1.60E-01	2.70E-04	4.20E-11	2.74E+02	6.70E-02	8.36E-04	1.30E-10
TOTAL						6.18E-01	9.57E-08

17•

AVERAGE CPG - INGESTION OF
 DRINKING WATER FROM A CONTAMINATED WELL
 for: Water Treat Sludge (Fertilizer)
 G= 7.40E+00
 S= 2.58E+02

$$D(\text{mrem}) = (G \cdot S \cdot C \cdot \text{DFing} \cdot (1-\exp)) / R$$

$$R(\text{fatal cancers}) = (G \cdot S \cdot C \cdot \text{RFing} \cdot (1-\exp)) / R$$

Nuclide	C	DFing	RFing	R	1-exp	D	R
Po-210	4.00E-01	1.90E-03	2.90E-10	2.73E+03	8.70E-03	4.62E-06	7.06E-13
Pb-210	4.00E-01	5.40E-03	8.40E-10	4.91E+03	8.70E-03	7.31E-06	1.14E-12
Ra-226	6.40E-01	1.30E-03	2.00E-10	2.45E+03	8.70E-03	5.64E-06	8.68E-13
Th-228	8.00E-03	4.00E-04	6.20E-11	8.18E+05	8.70E-03	6.50E-11	1.01E-17
Ra-228	8.00E-01	1.40E-03	2.20E-10	2.45E+03	8.70E-03	7.59E-06	1.19E-12
Th-230	8.00E-03	5.50E-04	8.50E-11	8.18E+05	8.70E-03	8.93E-11	1.38E-17
Th-232	8.00E-03	2.70E-03	4.20E-10	8.18E+05	8.70E-03	4.39E-10	6.82E-17
U-234	1.60E-01	2.80E-04	4.30E-11	2.45E+03	8.70E-03	3.04E-07	4.66E-14
U-238	1.60E-01	2.50E-04	3.90E-11	2.45E+03	8.70E-03	2.71E-07	4.23E-14
U-235	1.20E-03	2.70E-04	4.20E-11	2.45E+03	8.70E-03	2.20E-09	3.42E-16
TOTAL						2.57E-05	3.99E-12

**AVERAGE CPG - INGESTION OF
DRINKING WATER FROM A CONTAMINATED WELL
for: Water Treat Sludge (Landfill)
G= 7.40E+00
S= 8.50E+03**

$$D(\text{mrem}) = (G \cdot S \cdot C \cdot \text{DFing} \cdot (1-\exp)) / R$$

$$R(\text{fatal cancers}) = (G \cdot S \cdot C \cdot \text{RFing} \cdot (1-\exp)) / R$$

Nuclide	C	DFing	RFing	R	1-exp	D	R
Po-210	1.50E-01	1.90E-03	2.90E-10	2.73E+03	2.20E-04	1.44E-06	2.20E-13
Pb-210	1.50E-01	5.40E-03	8.40E-10	4.91E+03	2.20E-04	2.28E-06	3.55E-13
Ra-226	2.40E-01	1.30E-03	2.00E-10	2.45E+03	2.20E-04	1.76E-06	2.71E-13
Th-228	3.00E-03	4.00E-04	6.20E-11	8.18E+05	2.20E-04	2.03E-11	3.15E-18
Ra-228	3.00E-01	1.40E-03	2.20E-10	2.45E+03	2.20E-04	2.37E-06	3.73E-13
Th-230	3.00E-03	5.50E-04	8.50E-11	8.18E+05	2.20E-04	2.79E-11	4.31E-18
Th-232	3.00E-03	2.70E-03	4.20E-10	8.18E+05	2.20E-04	1.37E-10	2.13E-17
U-234	6.00E-02	2.80E-04	4.30E-11	2.45E+03	2.20E-04	9.49E-08	1.46E-14
U-238	6.00E-02	2.50E-04	3.90E-11	2.45E+03	2.20E-04	8.47E-08	1.32E-14
U-235	5.00E-04	2.70E-04	4.20E-11	2.45E+03	2.20E-04	7.63E-10	1.19E-16
TOTAL						8.04E-06	1.25E-12

17g

**AVERAGE CPG - INGESTION OF
DRINKING WATER FROM A CONTAMINATED WELL
for: Mineral Processing Waste
G= 7.40E+00
S= 3.06E+05**

$$D(\text{mrem}) = (G \cdot S \cdot C \cdot DF_{\text{ing}} \cdot (1 - \exp)) / R$$

$$R(\text{fatal cancers}) = (G \cdot S \cdot C \cdot RF_{\text{ing}} \cdot (1 - \exp)) / R$$

Nuclide	C	DFing	RFing	R	1-exp	D	R
Po-210	2.50E+01	1.90E-03	2.90E-10	2.74E+02	2.00E-06	85E-04	1.20E-10
Pb-210	2.50E+01	5.40E-03	8.40E-10	4.92E+02	2.00E-06	24E-03	1.93E-10
Ra-226	3.50E+01	1.30E-03	2.00E-10	2.46E+02	2.00E-06	38E-04	1.29E-10
Th-228	1.00E+01	4.00E-04	6.20E-11	8.18E+04	2.00E-06	21E-07	3.43E-14
Ra-228	1.00E+01	1.40E-03	2.20E-10	2.46E+02	2.00E-06	58E-04	4.05E-11
Th-230	3.50E+01	5.50E-04	8.50E-11	8.18E+04	2.00E-06	07E-06	1.65E-13
Th-232	1.00E+01	2.70E-03	4.20E-10	8.18E+04	2.00E-06	49E-06	2.33E-13
U-234	3.50E+01	2.80E-04	4.30E-11	2.46E+02	2.00E-06	80E-04	2.77E-11
U-238	3.50E+01	2.50E-04	3.90E-11	2.46E+03	2.00E-06	61E-05	2.51E-12
U-235	1.80E+00	2.70E-04	4.20E-11	2.46E+02	2.00E-06	95E-06	1.39E-12
TOTAL						33E-03	5.15E-10

17h

**AVERAGE CPG - INGESTION OF
DRINKING WATER FROM A CONTAMINATED WELL
for: Oil & Gas Scale/ Sludge
G= 7.40E+00
S= 3.96E+04**

$$D(\text{mrem}) = (G \cdot S \cdot C \cdot \text{DFing} \cdot (1 - \exp)) / R$$

$$R(\text{fatal cancers}) = (G \cdot S \cdot C \cdot \text{RFing} \cdot (1 - \exp)) / R$$

Nuclide	C	DFing	RFing	R	1-exp	D	R
Po-210	1.55E+02	1.90E-03	2.90E-10	5.46E+02	3.00E-03	4.74E-01	7.24E-08
Pb-210	1.55E+02	5.40E-03	8.40E-10	5.46E+02	3.00E-03	1.35E+00	2.10E-07
Ra-226	1.55E+02	1.30E-03	2.00E-10	1.36E+04	3.00E-03	1.30E-02	2.00E-09
Th-228	5.50E+01	4.00E-04	6.20E-11	1.36E+04	3.00E-03	1.42E-03	2.20E-10
Ra-228	5.50E+01	1.40E-03	2.20E-10	1.36E+04	3.00E-03	4.98E-03	7.82E-10
Th-230	--	--	--	--	--	--	--
Th-232	--	--	--	--	--	--	--
U-234	--	--	--	--	--	--	--
U-238	--	--	--	--	--	--	--
U-235	--	--	--	--	--	--	--
TOTAL						1.84E+00	2.85E-07

**AVERAGE CPG - INGESTION OF
DRINKING WATER FROM A CONTAMINATED WELL
for: Geothermal Waste
G= 7.40E+00
S= 9.25E+04**

$$D(\text{mrem}) = (G \cdot S \cdot C \cdot D\text{Fing} \cdot (1-\text{exp})) / R$$

$$R(\text{fatal cancers}) = (G \cdot S \cdot C \cdot R\text{Fing} \cdot (1-\text{exp})) /$$

Nuclide	C	D _{Fing}	R _{Fing}	R	1-exp	D	R
Po-210	1.10E+02	1.90E-03	2.90E-10	2.74E+02	5.80E-05	3.03E-02	4.62E-09
Pb-210	1.10E+02	5.40E-03	8.40E-10	4.92E+02	5.80E-05	4.79E-02	7.46E-09
Ra-226	1.60E+02	1.30E-03	2.00E-10	2.46E+02	5.80E-05	3.36E-02	5.16E-09
Th-228	3.00E+01	4.00E-04	6.20E-11	8.18E+04	5.80E-05	5.82E-06	9.03E-13
Ra-228	1.10E+02	1.40E-03	2.20E-10	2.46E+02	5.80E-05	2.49E-02	3.91E-09
Th-230	--	--	--	--	--	--	--
Th-232	--	--	--	--	--	--	--
U-234	--	--	--	--	--	--	--
U-238	--	--	--	--	--	--	--
U-235	--	--	--	--	--	--	--
TOTAL						1.37E-01	2.11E-08

8a

**AVG CPG - INGESTION OF FOODSTUFFS
CONTAMINATED BY WELL WATER**

for: Uranium Overburden

G= 2.00E+01

S= 4.67E+04

1-exp= 3.40E-05

D(mrem) = (G * S * C * (Uw - 0.37) * DFing * (1-exp)) / R

R(fatal cancers) = (G * S * C * (Uw - 0.37) * RFing * (1-exp)) / R

Nuclide	C	DFing	RFing	R	Uw	D	R
Po-210	1.66E+01	1.90E-03	2.90E-10	2.74E+02	9.43E-01	2.09E-03	3.20E-10
Pb-210	1.66E+01	5.40E-03	8.40E-10	4.92E+02	9.43E-01	3.32E-03	5.16E-10
Ra-226	2.37E+01	1.30E-03	2.00E-10	2.46E+02	9.43E-01	2.28E-03	3.51E-10
Th-228	1.00E+00	4.00E-04	6.20E-11	8.18E+04	9.39E-01	8.84E-08	1.37E-14
Ra-228	1.00E+00	1.40E-03	2.20E-10	2.46E+02	9.39E-01	1.03E-04	1.62E-11
Th-230	2.37E+01	5.50E-04	8.50E-11	8.18E+04	9.43E-01	2.90E-06	4.48E-13
Th-232	1.00E+00	2.70E-03	4.20E-10	8.18E+04	9.39E-01	5.96E-07	9.28E-14
U-234	2.37E+01	2.80E-04	4.30E-11	2.46E+02	8.76E-01	4.33E-04	6.66E-11
U-238	2.37E+01	2.50E-04	3.90E-11	2.46E+02	8.76E-01	3.87E-04	6.04E-11
U-235	1.20E+00	2.70E-04	4.20E-11	2.46E+02	8.76E-01	2.12E-05	3.29E-12
TOTAL						8.64E-03	1.33E-09

18b

**AVG CPQ - INGESTION OF FOODSTUFFS
CONTAMINATED BY WELL WATER**

for: Phosphate Waste

G= 2.00E+01

S= 7.72E+03

1-exp= 3.50E-02

D(mrem) = (G * S * C * (Uw - 0.37) * DFing * (1-exp)) / R

R(fatal cancers) = (G * S * C * (Uw - 0.37) * RFing * (1-exp)) / R

Nuclide	C	DFing	RFing	R	Uw	D	R
Po-210	2.64E+01	1.90E-03	2.90E-10	2.73E+03	9.43E-01	5.69E-02	8.68E-09
Pb-210	2.64E+01	5.40E-03	8.40E-10	4.91E+03	9.43E-01	8.99E-02	1.40E-08
Ra-226	3.30E+01	1.30E-03	2.00E-10	2.45E+03	9.43E-01	5.42E-02	8.34E-09
Th-228	2.70E-01	4.00E-04	6.20E-11	8.18E+05	9.39E-01	4.06E-07	6.29E-14
Ra-228	2.70E-01	1.40E-03	2.20E-10	2.45E+03	9.39E-01	4.74E-04	7.46E-11
Th-230	1.30E+01	5.50E-04	8.50E-11	8.18E+05	9.43E-01	2.71E-05	4.18E-12
Th-232	2.70E-01	2.70E-03	4.20E-10	8.18E+05	9.39E-01	2.74E-06	4.26E-13
U-234	6.20E+00	2.80E-04	4.30E-11	2.45E+03	8.76E-01	1.94E-03	2.98E-10
U-238	6.00E+00	2.50E-04	3.90E-11	2.45E+03	8.76E-01	1.67E-03	2.61E-10
U-235	3.00E-01	2.70E-04	4.20E-11	2.45E+03	8.76E-01	9.04E-05	1.41E-11
TOTAL						2.05E-01	3.17E-08

18c

AVG CPG - INGESTION OF FOODSTUFFS
CONTAMINATED BY WELL WATER

Phosphate Fertilizer

G= 2.00E+01

S= 2.18E+02

1-exp= 8.80E-03

$D(\text{mrem}) = (G \cdot S \cdot C \cdot (Uw - 0.37) \cdot DFing \cdot (1-exp)) / R$

$R(\text{fatal cancers}) = (G \cdot S \cdot C \cdot (Uw - 0.37) \cdot RFing \cdot (1-exp)) / R$

Nuclide	C	DFing	RFing	R	Uw	D	R
Po-210	1.80E-03	1.90E-03	2.90E-10	2.73E+03	9.43E-01	2.75E-08	4.20E-15
Pb-210	1.80E-03	5.40E-03	8.40E-10	4.91E+03	9.43E-01	4.35E-08	6.77E-15
Ra-226	2.50E-03	1.30E-03	2.00E-10	2.45E+03	9.43E-01	2.92E-08	4.49E-15
Th-228	3.40E-04	4.00E-04	6.20E-11	8.18E+05	9.39E-01	3.63E-12	5.63E-19
Ra-228	3.40E-04	1.40E-03	2.20E-10	2.45E+03	9.39E-01	4.24E-09	6.67E-16
Th-230	1.60E-02	5.50E-04	8.50E-11	8.18E+05	9.43E-01	2.37E-10	3.66E-17
Th-232	3.10E-04	2.70E-03	4.20E-10	8.18E+05	9.39E-01	2.23E-11	3.47E-18
U-234	1.70E-02	2.80E-04	4.30E-11	2.45E+03	8.76E-01	3.77E-08	5.79E-15
U-238	1.70E-02	2.50E-04	3.90E-11	2.45E+03	8.76E-01	3.37E-08	5.25E-15
U-235	8.60E-04	2.70E-04	4.20E-11	2.45E+03	8.76E-01	1.84E-09	2.86E-16
TOTAL						1.78E-07	2.75E-14

18d

**AVG CPG - INGESTION OF FOODSTUFFS
CONTAMINATED BY WELL WATER**

for: Coal Ash

G= 2.00E+01

S= 1.07E+04

1-exp= 6.70E-02

D(mrem) = (G * S * C * (Uw - 0.37) * DFing * (1-exp)) / R

R(fatal cancers) = (G * S * C * (Uw - 0.37) * RFing * (1-exp)) / R

Nuclide	C	DFing	RFing	R	Uw	D	R
Po-210	7.00E+00	1.90E-03	2.90E-10	5.46E+02	9.43E-01	2.00E-01	3.05E-08
Pb-210	6.80E+00	5.40E-03	8.40E-10	5.46E+02	9.43E-01	5.53E-01	8.59E-08
Ra-226	3.70E+00	1.30E-03	2.00E-10	4.10E+02	9.43E-01	9.64E-02	1.48E-08
Th-228	3.20E+00	4.00E-04	6.20E-11	1.64E+04	9.39E-01	6.37E-04	9.87E-11
Ra-228	1.80E+00	1.40E-03	2.20E-10	4.10E+02	9.39E-01	5.01E-02	7.88E-09
Th-230	2.30E+00	5.50E-04	8.50E-11	1.64E+04	9.43E-01	6.34E-04	9.79E-11
Th-232	2.10E+00	2.70E-03	4.20E-10	1.64E+04	9.39E-01	2.82E-03	4.39E-10
U-234	3.30E+00	2.80E-04	4.30E-11	2.74E+02	8.76E-01	2.45E-02	3.76E-09
U-238	3.30E+00	2.50E-04	3.90E-11	2.74E+02	8.76E-01	2.18E-02	3.41E-09
U-235	1.60E-01	2.70E-04	4.20E-11	2.74E+02	8.76E-01	1.14E-03	1.78E-10
					TOTAL	9.51E-01	1.47E-07

**AVG CPG - INGESTION OF FOODSTUFFS
CONTAMINATED BY WELL WATER**

for: Water Treat Sludge (Fertilizer)

$$G = 2.00E+01$$

$$S = 2.58E+02$$

$$1-\exp = 8.70E-03$$

$$D(\text{mrem}) = (G \cdot S \cdot C \cdot (Uw - 0.37) \cdot DFing \cdot (1-\exp)) / R$$

$$R(\text{fatal cancers}) = (G \cdot S \cdot C \cdot (Uw - 0.37) \cdot RFing \cdot (1-\exp)) / R$$

Nuclide	C	DFing	RFing	R	Uw	D	R
Po-210	4.00E-01	1.90E-03	2.90E-10	2.73E+03	9.43E-01	7.16E-06	1.09E-12
Pb-210	4.00E-01	5.40E-03	8.40E-10	4.91E+03	9.43E-01	1.13E-05	1.76E-12
Ra-226	6.40E-01	1.30E-03	2.00E-10	2.45E+03	9.43E-01	8.74E-06	1.34E-12
Th-228	8.00E-03	4.00E-04	6.20E-11	8.18E+05	9.39E-01	9.99E-11	1.55E-17
Ra-228	8.00E-01	1.40E-03	2.20E-10	2.45E+03	9.39E-01	1.17E-05	1.83E-12
Th-230	8.00E-03	5.50E-04	8.50E-11	8.18E+05	9.43E-01	1.38E-10	2.14E-17
Th-232	8.00E-03	2.70E-03	4.20E-10	8.18E+05	9.39E-01	6.74E-10	1.05E-16
U-234	1.60E-01	2.80E-04	4.30E-11	2.45E+03	8.76E-01	4.15E-07	6.38E-14
U-238	1.60E-01	2.50E-04	3.90E-11	2.45E+03	8.76E-01	3.71E-07	5.79E-14
U-235	1.20E-03	2.70E-04	4.20E-11	2.45E+03	8.76E-01	3.00E-09	4.67E-16
TOTAL						3.97E-05	6.15E-12

**AVG CPG - INGESTION OF FOODSTUFFS
CONTAMINATED BY WELL WATER**

for: Water Treat Sludge (Landfill)

G= 2.00E+01

S= 8.50E+03

1-exp= 2.20E-04

D(mrem) = (G * S * C * (Uw - 0.37) * DFing * (1-exp)) / R

R(fatal cancers) = (G * S * C * (Uw - 0.37) * RFing * (1-exp)) / R

Nuclide	C	DFing	RFing	R	Uw	D	R
Po-210	1.50E-01	1.90E-03	2.90E-10	2.73E+03	9.43E-01	2.24E-06	3.41E-13
Pb-210	1.50E-01	5.40E-03	8.40E-10	4.91E+03	9.43E-01	3.54E-06	5.50E-13
Ra-226	2.40E-01	1.30E-03	2.00E-10	2.45E+03	9.43E-01	2.73E-06	4.20E-13
Th-228	3.00E-03	4.00E-04	6.20E-11	8.18E+05	9.39E-01	3.12E-11	4.84E-18
Ra-228	3.00E-01	1.40E-03	2.20E-10	2.45E+03	9.39E-01	3.65E-06	5.73E-13
Th-230	3.00E-03	5.50E-04	8.50E-11	8.18E+05	9.43E-01	4.32E-11	6.68E-18
Th-232	3.00E-03	2.70E-03	4.20E-10	8.18E+05	9.39E-01	2.11E-10	3.28E-17
U-234	6.00E-02	2.80E-04	4.30E-11	2.45E+03	8.76E-01	1.30E-07	1.99E-14
U-238	6.00E-02	2.50E-04	3.90E-11	2.45E+03	8.76E-01	1.16E-07	1.81E-14
U-235	5.00E-04	2.70E-04	4.20E-11	2.45E+03	8.76E-01	1.04E-09	1.62E-16
TOTAL						1.24E-05	1.92E-12

18g

**AVG CPG - INGESTION OF FOODSTUFFS
CONTAMINATED BY WELL WATER
for: Mineral Processing Waste**

G= 2.00E+01

S= 3.06E+05

1-exp= 2.00E-06

D(mrem) = (G * S * C * (Uw - 0.37) * DFing * (1-exp)) / R

R(fatal cancers) = (G * S * C * (Uw - 0.37) * RFing * (1-exp)) / R

Nuclide	C	DFing	RFing	R	Uw	D	R
Po-210	2.50E+01	1.90E-03	2.90E-10	2.74E+02	9.43E-01	1.22E-03	1.86E-10
Pb-210	2.50E+01	5.40E-03	8.40E-10	4.92E+02	9.43E-01	1.92E-03	2.99E-10
Ra-226	3.50E+01	1.30E-03	2.00E-10	2.46E+02	9.43E-01	1.30E-03	2.00E-10
Th-228	1.00E+01	4.00E-04	6.20E-11	8.18E+04	9.39E-01	3.41E-07	5.28E-14
Ra-228	1.00E+01	1.40E-03	2.20E-10	2.46E+02	9.39E-01	3.96E-04	6.23E-11
Th-230	3.50E+01	5.50E-04	8.50E-11	8.18E+04	9.43E-01	1.65E-06	2.55E-13
Th-232	1.00E+01	2.70E-03	4.20E-10	8.18E+04	9.39E-01	2.30E-06	3.58E-13
U-234	3.50E+01	2.80E-04	4.30E-11	2.46E+02	8.76E-01	2.47E-04	3.79E-11
U-238	3.50E+01	2.50E-04	3.90E-11	2.46E+03	8.76E-01	2.20E-05	3.44E-12
U-235	1.80E+00	2.70E-04	4.20E-11	2.46E+02	8.76E-01	1.22E-05	1.90E-12
TOTAL						5.12E-03	7.91E-10

18h

**AVG CPG - INGESTION OF FOODSTUFFS
CONTAMINATED BY WELL WATER
for: Oil & Gas Scale/ Sludge**

G= 2.00E+01

S= 3.96E+04

1-exp= 3.00E-03

D(mrem) = (G * S * C * (Uw - 0.37) * DFing * (1-exp)) / R

R(fatal cancers) = (G * S * C * (Uw - 0.37) * RFing * (1-exp)) / R

Nuclide	C	DFing	RFing	R	Uw	D	R
Po-210	1.55E+02	1.90E-03	2.90E-10	5.46E+02	9.43E-01	7.34E-01	1.12E-07
Pb-210	1.55E+02	5.40E-03	8.40E-10	5.46E+02	9.43E-01	2.09E+00	3.25E-07
Ra-226	1.55E+02	1.30E-03	2.00E-10	1.36E+04	9.43E-01	2.02E-02	3.10E-09
Th-228	5.50E+01	4.00E-04	6.20E-11	1.36E+04	9.39E-01	2.19E-03	3.39E-10
Ra-228	5.50E+01	1.40E-03	2.20E-10	1.36E+04	9.39E-01	7.65E-03	1.20E-09
Th-230	--	--	--	--	--	--	--
Th-232	--	--	--	--	--	--	--
U-234	--	--	--	--	--	--	--
U-238	--	--	--	--	--	--	--
U-235	--	--	--	--	--	--	--
TOTAL						2.85E+00	4.41E-07

**AVG CPG - INGESTION OF FOODSTUFFS
CONTAMINATED BY WELL WATER**

for: Geothermal Waste

G= 2.00E+01

S= 9.25E+04

1-exp= 5.80E-05

D(mrem) = (G * S * C * (Uw - 0.37) * DFing * (1-exp)) / R

R(fatal cancers) = (G * S * C * (Uw - 0.37) * RFing * (1-exp)) / R

Nuclide	C	DFing	RFing	R	Uw	D	R
Po-210	1.10E+02	1.90E-03	2.90E-10	2.74E+02	9.43E-01	4.69E-02	7.16E-09
Pb-210	1.10E+02	5.40E-03	8.40E-10	4.92E+02	9.43E-01	7.42E-02	1.15E-08
Ra-226	1.60E+02	1.30E-03	2.00E-10	2.46E+02	9.43E-01	5.20E-02	8.00E-09
Th-228	3.00E+01	4.00E-04	6.20E-11	8.18E+04	9.39E-01	8.96E-06	1.39E-12
Ra-228	1.10E+02	1.40E-03	2.20E-10	2.46E+02	9.39E-01	3.82E-02	6.01E-09
Th-230	--	--	--	--	--	--	--
Th-232	--	--	--	--	--	--	--
U-234	--	--	--	--	--	--	--
U-238	--	--	--	--	--	--	--
U-235	--	--	--	--	--	--	--
TOTAL						2.11E-01	3.27E-08

19a

**AVERAGE CPG - INGESTION OF
FOODSTUFFS CONTAMINATED BY DUST DEPOSITION
for: Uranium Overburden
G= 2.66E+02
S= 6.90E-07**

$$D(\text{mrem}) = G \cdot S \cdot C \cdot \text{DFing} \cdot \text{Uf}$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot \text{RFing} \cdot \text{Uf}$$

Nuclide	C	DFing	RFing	Uf	D	R
Po-210	1.66E+01	1.90E-03	2.90E-10	1.31E-02	7.58E-08	1.16E-14
Pb-210	1.66E+01	5.40E-03	8.40E-10	1.31E-02	2.16E-07	3.35E-14
Ra-226	2.37E+01	1.30E-03	2.00E-10	1.31E-02	7.41E-08	1.14E-14
Th-228	1.00E+00	4.00E-04	6.20E-11	1.29E-02	9.47E-10	1.47E-16
Ra-228	1.00E+00	1.40E-03	2.20E-10	1.29E-02	3.31E-09	5.21E-16
Th-230	2.37E+01	5.50E-04	8.50E-11	1.31E-02	3.13E-08	4.84E-15
Th-232	1.00E+00	2.70E-03	4.20E-10	1.29E-02	6.39E-09	9.94E-16
U-234	2.37E+01	2.80E-04	4.30E-11	2.21E-02	2.69E-08	4.13E-15
U-238	2.37E+01	2.50E-04	3.90E-11	2.21E-02	2.40E-08	3.75E-15
U-235	1.20E+00	2.70E-04	4.20E-11	2.21E-02	1.31E-09	2.04E-16
TOTAL					4.60E-07	7.11E-14

19b

**AVERAGE CPG - INGESTION OF
FOODSTUFFS CONTAMINATED BY DUST DEPOSITION
for: Phosphate Waste
G= 2.66E+02
S= 2.83E-07**

$$D(\text{mrem}) = G \cdot S \cdot C \cdot \text{DFing} \cdot \text{Uf}$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot \text{RFing} \cdot \text{Uf}$$

Nuclide	C	DFing	RFing	Uf	D	R
Po-210	2.64E+01	1.90E-03	2.90E-10	1.31E-02	4.95E-08	7.55E-15
Pb-210	2.64E+01	5.40E-03	8.40E-10	1.31E-02	1.41E-07	2.19E-14
Ra-226	3.30E+01	1.30E-03	2.00E-10	1.31E-02	4.23E-08	6.51E-15
Th-228	2.70E-01	4.00E-04	6.20E-11	1.29E-02	1.05E-10	1.63E-17
Ra-228	2.70E-01	1.40E-03	2.20E-10	1.29E-02	3.67E-10	5.77E-17
Th-230	1.30E+01	5.50E-04	8.50E-11	1.31E-02	7.05E-09	1.09E-15
Th-232	2.70E-01	2.70E-03	4.20E-10	1.29E-02	7.08E-10	1.10E-16
U-234	6.20E+00	2.80E-04	4.30E-11	2.21E-02	2.89E-09	4.44E-16
U-238	6.00E+00	2.50E-04	3.90E-11	2.21E-02	2.50E-09	3.89E-16
U-235	3.00E-01	2.70E-04	4.20E-11	2.21E-02	1.35E-10	2.10E-17
TOTAL					2.46E-07	3.81E-14

19c

**AVERAGE CPG - INGESTION OF
FOODSTUFFS CONTAMINATED BY DUST DEPOSITION
Phosphate Fertilizer
G= 2.66E+02
S= 6.90E-07**

$$D(\text{mrem}) = G \cdot S \cdot C \cdot \text{DFing} \cdot \text{Uf}$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot \text{RFing} \cdot \text{Uf}$$

Nuclide	C	DFing	RFing	Uf	D	R
Po-210	1.80E-03	1.90E-03	2.90E-10	1.31E-02	8.22E-12	1.26E-18
Pb-210	1.80E-03	5.40E-03	8.40E-10	1.31E-02	2.34E-11	3.64E-18
Ra-226	2.50E-03	1.30E-03	2.00E-10	1.31E-02	7.81E-12	1.20E-18
Th-228	3.40E-04	4.00E-04	6.20E-11	1.29E-02	3.22E-13	4.99E-20
Ra-228	3.40E-04	1.40E-03	2.20E-10	1.29E-02	1.13E-12	1.77E-19
Th-230	1.60E-02	5.50E-04	8.50E-11	1.31E-02	2.12E-11	3.27E-18
Th-232	3.10E-04	2.70E-03	4.20E-10	1.29E-02	1.98E-12	3.08E-19
U-234	1.70E-02	2.80E-04	4.30E-11	2.21E-02	1.93E-11	2.97E-18
U-238	1.70E-02	2.50E-04	3.90E-11	2.21E-02	1.72E-11	2.69E-18
U-235	8.60E-04	2.70E-04	4.20E-11	2.21E-02	9.42E-13	1.47E-19
TOTAL					1.01E-10	1.57E-17

**AVERAGE CPQ - INGESTION OF
FOODSTUFFS CONTAMINATED BY DUST DEPOSITION**

for: Coal Ash

G= 2.66E+02

S= 1.32E-07

D(mrem) = G * S * C * DFing * Uf

R(fatal cancers) = G * S * C * RFing * Uf

Nuclide	C	DFing	RFing	Uf	D	R
Po-210	7.00E+00	1.90E-03	2.90E-10	1.31E-02	6.12E-09	9.34E-16
Pb-210	6.80E+00	5.40E-03	8.40E-10	1.31E-02	1.69E-08	2.63E-15
Ra-226	3.70E+00	1.30E-03	2.00E-10	1.31E-02	2.21E-09	3.40E-16
Th-228	3.20E+00	4.00E-04	6.20E-11	1.29E-02	5.80E-10	8.99E-17
Ra-228	1.80E+00	1.40E-03	2.20E-10	1.29E-02	1.14E-09	1.79E-16
Th-230	2.30E+00	5.50E-04	8.50E-11	1.31E-02	5.82E-10	8.99E-17
Th-232	2.10E+00	2.70E-03	4.20E-10	1.29E-02	2.57E-09	3.99E-16
U-234	3.30E+00	2.80E-04	4.30E-11	2.21E-02	7.17E-10	1.10E-16
U-238	3.30E+00	2.50E-04	3.90E-11	2.21E-02	6.40E-10	9.99E-17
U-235	1.60E-01	2.70E-04	4.20E-11	2.21E-02	3.35E-11	5.21E-18
TOTAL					3.15E-08	4.88E-15

**AVERAGE CPG - INGESTION OF
FOODSTUFFS CONTAMINATED BY DUST DEPOSITION
for: Water Treat Sludge (Fertilizer)**
G= 2.66E+02
S= 8.28E-07

$$D(\text{mrem}) = G \cdot S \cdot C \cdot DF_{\text{ing}} \cdot Uf$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot RF_{\text{ing}} \cdot Uf$$

Nuclide	C	DF _{ing}	RF _{ing}	Uf	D	R
Po-210	4.00E-01	1.90E-03	2.90E-10	1.31E-02	2.19E-09	3.35E-16
Pb-210	4.00E-01	5.40E-03	8.40E-10	1.31E-02	6.23E-09	9.69E-16
Ra-226	6.40E-01	1.30E-03	2.00E-10	1.31E-02	2.40E-09	3.69E-16
Th-228	8.00E-03	4.00E-04	6.20E-11	1.29E-02	9.09E-12	1.41E-18
Ra-228	8.00E-01	1.40E-03	2.20E-10	1.29E-02	3.18E-09	5.00E-16
Th-230	8.00E-03	5.50E-04	8.50E-11	1.31E-02	1.27E-11	1.96E-18
Th-232	8.00E-03	2.70E-03	4.20E-10	1.29E-02	6.14E-11	9.55E-18
U-234	1.60E-01	2.80E-04	4.30E-11	2.21E-02	2.18E-10	3.35E-17
U-238	1.60E-01	2.50E-04	3.90E-11	2.21E-02	1.95E-10	3.04E-17
U-235	1.20E-03	2.70E-04	4.20E-11	2.21E-02	1.58E-12	2.45E-19
TOTAL					1.45E-08	2.25E-15

**AVERAGE CPD - INGESTION OF
FOODSTUFFS CONTAMINATED BY DUST DEPOSITION
for: Water Treat Sludge (Landfill)**
G= 2.66E+02
S= 8.95E-07

$$D(\text{mrem}) = G \cdot S \cdot C \cdot DF_{\text{ing}} \cdot Uf$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot RF_{\text{ing}} \cdot Uf$$

Nuclide	C	DF _{ing}	RF _{ing}	f	D	R
Po-210	1.50E-01	1.90E-03	2.90E-10	1.3E-02	8.89E-10	1.36E-16
Pb-210	1.50E-01	5.40E-03	8.40E-10	1.3E-02	2.53E-09	3.93E-16
Ra-226	2.40E-01	1.30E-03	2.00E-10	1.3E-02	9.73E-10	1.50E-16
Th-228	3.00E-03	4.00E-04	6.20E-11	1.2E-02	3.69E-12	5.71E-19
Ra-228	3.00E-01	1.40E-03	2.20E-10	1.2E-02	1.29E-09	2.03E-16
Th-230	3.00E-03	5.50E-04	8.50E-11	1.3E-02	5.15E-12	7.95E-19
Th-232	3.00E-03	2.70E-03	4.20E-10	1.2E-02	2.49E-11	3.87E-18
U-234	6.00E-02	2.80E-04	4.30E-11	2.2E-02	8.84E-11	1.36E-17
U-238	6.00E-02	2.50E-04	3.90E-11	2.2E-02	7.89E-11	1.23E-17
U-235	5.00E-04	2.70E-04	4.20E-11	2.2E-02	7.10E-13	1.10E-19
TOTAL					5.88E-09	9.12E-16

**AVERAGE CPG - INGESTION OF
FOODSTUFFS CONTAMINATED BY DUST DEPOSITION
for: Mineral Processing Waste**

$$G = 2.66E+02$$

$$S = 6.85E-07$$

$$D(\text{mrem}) = G \cdot S \cdot C \cdot DF_{\text{ing}} \cdot Uf$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot RF_{\text{ing}} \cdot Uf$$

Nuclide	C	DF _{ing}	RF _{ing}	Uf	D	R
Po-210	2.50E+01	1.90E-03	2.90E-10	1.31E-02	1.13E-07	1.73E-14
Pb-210	2.50E+01	5.40E-03	8.40E-10	1.31E-02	3.22E-07	5.01E-14
Ra-226	3.50E+01	1.30E-03	2.00E-10	1.31E-02	1.09E-07	1.67E-14
Th-228	1.00E+01	4.00E-04	6.20E-11	1.29E-02	9.40E-09	1.46E-15
Ra-228	1.00E+01	1.40E-03	2.20E-10	1.29E-02	3.29E-08	5.17E-15
Th-230	3.50E+01	5.50E-04	8.50E-11	1.31E-02	4.59E-08	7.10E-15
Th-232	1.00E+01	2.70E-03	4.20E-10	1.29E-02	6.35E-08	9.87E-15
U-234	3.50E+01	2.80E-04	4.30E-11	2.21E-02	3.95E-08	6.06E-15
U-238	3.50E+01	2.50E-04	3.90E-11	2.21E-02	3.52E-08	5.50E-15
U-235	1.80E+00	2.70E-04	4.20E-11	2.21E-02	1.96E-09	3.04E-16
TOTAL					7.73E-07	1.20E-13

19h

**AVERAGE CPG - INGESTION OF
FOODSTUFFS CONTAMINATED BY DUST DEPOSITION
for: Oil & Gas Scale/ Sludge
G= 2.66E+02
S= 6.39E-08**

$$D(\text{mrem}) = G \cdot S \cdot C \cdot DF_{\text{ing}} \cdot Uf$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot RF_{\text{ing}} \cdot Uf$$

Nuclide	C	DFing	RFing	Uf	D	R
Po-210	1.55E+02	1.90E-03	2.90E-10	1.31E-02	6.56E-08	1.00E-14
Pb-210	1.55E+02	5.40E-03	8.40E-10	1.31E-02	1.86E-07	2.90E-14
Ra-226	1.55E+02	1.30E-03	2.00E-10	1.31E-02	4.49E-08	6.90E-15
Th-228	5.50E+01	4.00E-04	6.20E-11	1.29E-02	4.82E-09	7.48E-16
Ra-228	5.50E+01	1.40E-03	2.20E-10	1.29E-02	1.69E-08	2.65E-15
Th-230	--	--	--	--	--	--
Th-232	--	--	--	--	--	--
U-234	--	--	--	--	--	--
U-238	--	--	--	--	--	--
U-235	--	--	--	--	--	--
TOTAL					3.19E-07	4.93E-14

**AVERAGE CPG - INGESTION OF
FOODSTUFFS CONTAMINATED BY DUST DEPOSITION
for: Geothermal Waste
G= 2.66E+02
S= 6.01E-08**

$$D(\text{mrem}) = G \cdot S \cdot C \cdot DF_{\text{ing}} \cdot U_f$$

$$R(\text{fatal cancers}) = G \cdot S \cdot C \cdot RF_{\text{ing}} \cdot U_f$$

Nuclide	C	DF _{ing}	RF _{ing}	U _f	D	R
Po-210	1.10E+02	1.90E-03	2.90E-10	1.31E-02	4.38E-08	6.68E-15
Pb-210	1.10E+02	5.40E-03	8.40E-10	1.31E-02	1.24E-07	1.94E-14
Ra-226	1.60E+02	1.30E-03	2.00E-10	1.31E-02	4.36E-08	6.70E-15
Th-228	3.00E+01	4.00E-04	6.20E-11	1.29E-02	2.47E-09	3.84E-16
Ra-228	1.10E+02	1.40E-03	2.20E-10	1.29E-02	3.18E-08	4.99E-15
Th-230	--	--	--	--	--	--
Th-232	--	--	--	--	--	--
U-234	--	--	--	--	--	--
U-238	--	--	--	--	--	--
U-235	--	--	--	--	--	--
TOTAL					2.46E-07	3.81E-14

119c

**OTHER INDIVIDUAL - INGESTION OF FOODSTUFFS GROWN ON
REPEATEDLY FERTILIZED SOIL**

for: Phosphate Fertilizer

G= 1.00E+03

S= 1.00E+00

D(mrem) = G * S * C * DFing * Uf

R(fatal cancers) = G * S * C * RFing * Uf

Nuclide	C	DFing	RFing	Uf	D	R
Po-210	1.80E-03	1.90E-03	2.90E-10	1.31E-02	4.48E-05	6.84E-12
Pb-210	1.80E-03	5.40E-03	8.40E-10	1.31E-02	1.27E-04	1.98E-11
Ra-226	2.50E-03	1.30E-03	2.00E-10	1.31E-02	4.26E-05	6.55E-12
Th-228	3.40E-04	4.00E-04	6.20E-11	1.29E-02	1.75E-06	2.72E-13
Ra-228	3.40E-04	1.40E-03	2.20E-10	1.29E-02	6.14E-06	9.65E-13
Th-230	1.60E-02	5.50E-04	8.50E-11	1.31E-02	1.15E-04	1.78E-11
Th-232	3.10E-04	2.70E-03	4.20E-10	1.29E-02	1.08E-05	1.68E-12
U-234	1.70E-02	2.80E-04	4.30E-11	2.21E-02	1.05E-04	1.62E-11
U-238	1.70E-02	2.50E-04	3.90E-11	2.21E-02	9.39E-05	1.47E-11
U-235	8.60E-04	2.70E-04	4.20E-11	2.21E-02	5.13E-06	7.98E-13
TOTAL					5.53E-04	8.55E-11

110●

**OTHER INDIVIDUAL - INGESTION OF FOODSTUFFS GROWN ON
REPEATEDLY FERTILIZED SOIL**
for: Water Treat Sludge (Fertilizer)
G= 1.00E+03
S= 1.00E+00

D(mrem) = G * S * C * DFing * Uf
R(fatal cancers) = G * S * C * RFing * Uf

Nuclide	C	DFing	RFing	Uf	D	R
Po-210	4.00E-01	1.90E-03	2.90E-10	1.31E-02	9.96E-03	1.52E-09
Pb-210	4.00E-01	5.40E-03	8.40E-10	1.31E-02	2.83E-02	4.40E-09
Ra-226	6.40E-01	1.30E-03	2.00E-10	1.31E-02	1.09E-02	1.68E-09
Th-228	8.00E-03	4.00E-04	6.20E-11	1.29E-02	4.13E-05	6.40E-12
Ra-228	8.00E-01	1.40E-03	2.20E-10	1.29E-02	1.44E-02	2.27E-09
Th-230	8.00E-03	5.50E-04	8.50E-11	1.31E-02	5.76E-05	8.91E-12
Th-232	8.00E-03	2.70E-03	4.20E-10	1.29E-02	2.79E-04	4.33E-11
U-234	1.60E-01	2.80E-04	4.30E-11	2.21E-02	9.90E-04	1.52E-10
U-238	1.60E-01	2.50E-04	3.90E-11	2.21E-02	8.84E-04	1.38E-10
U-235	1.20E-03	2.70E-04	4.20E-11	2.21E-02	7.16E-06	1.11E-12
TOTAL					6.59E-02	1.02E-08

P1a

POP. - DOWNWIND EXPOSURE TO RESUSPENDED PARTICULATES
for: Uranium Overburden

$$G = 1.00E+03$$

$$G1 = 8.00E+03$$

$$G2 = 3.15E+05$$

$$G3 = 4.50E+02$$

$$S = 1.77E-06$$

$$PR(\text{fatal cancers}) = G \cdot S \cdot C \cdot [(G1 \cdot RFinh) + (G2 \cdot RFG) + (G3 \cdot Uf \cdot RFinh)]$$

$$PD(\text{person mrem}) = G \cdot S \cdot C \cdot [(G1 \cdot DFinh) + (G2 \cdot DFG) + (G3 \cdot Uf \cdot DFinh)]$$

Nuclide	Uf	C	DFinh	RFinh	DFinh	RFinh	PD	PR
Po-210	1.31E-02	1.66E+01	1.90E-03	2.90E-10	9.40E-03	1.50E-09	2.21E+00	3.53E-07
Pb-210	1.31E-02	1.66E+01	5.40E-03	8.40E-10	1.40E-02	2.20E-09	3.29E+00	5.18E-07
Ra-226	1.31E-02	2.37E+01	1.30E-03	2.00E-10	8.60E-03	1.30E-09	5.09E+00	1.30E-06
Th-228	1.29E-02	1.00E+00	4.00E-04	6.20E-11	3.40E-01	5.30E-08	5.00E+00	8.23E-07
Ra-228	1.29E-02	1.00E+00	1.40E-03	2.20E-10	4.80E-03	7.40E-10	1.18E-01	3.00E-08
Th-230	1.31E-02	2.37E+01	5.50E-04	8.50E-11	3.30E-01	5.10E-08	1.11E+02	1.71E-05
Th-232	1.29E-02	1.00E+00	2.70E-03	4.20E-10	1.60E+00	2.50E-07	2.27E+01	3.54E-06
U-234	2.21E-02	2.37E+01	2.80E-04	4.30E-11	1.30E-01	2.00E-08	4.36E+01	6.71E-06
U-238	2.21E-02	2.37E+01	2.50E-04	3.90E-11	1.20E-01	1.90E-08	4.03E+01	6.38E-06
U-235	2.21E-02	1.20E+00	2.70E-04	4.20E-11	1.20E-01	1.90E-08	2.05E+00	3.27E-07
TOTAL							2.35E+02	3.71E-05

P1b

POP. - DOWNWIND EXPOSURE TO RESUSPENDED PARTICULATES

for: Phosphate Waste

G= 1.00E+03

G1= 8.00E+03

G2= 3.15E+05

G3= 4.50E+02

S= 4.51E-06

PR(fatal cancers) = G * S * C * [(G1*RFInh) + (G2*RFG) + (G3*Uf*RFInh)]

PD(person mrem) = G * S * C * [(G1*DFInh) + (G2*DFG) + (G3*Uf*DFInh)]

Nuclide	Uf	C	DFInh	RFInh	DFInh	RFInh	PD	PR
Po-210	1.31E-02	2.64E+01	1.90E-03	2.90E-10	9.40E-03	1.50E-09	8.95E+00	1.43E-06
Pb-210	1.31E-02	2.64E+01	5.40E-03	8.40E-10	1.40E-02	2.20E-09	1.33E+01	2.10E-06
Ra-226	1.31E-02	3.30E+01	1.30E-03	2.00E-10	8.60E-03	1.30E-09	1.81E+01	4.60E-06
Th-228	1.29E-02	2.70E-01	4.00E-04	6.20E-11	3.40E-01	5.30E-08	3.44E+00	5.66E-07
Ra-228	1.29E-02	2.70E-01	1.40E-03	2.20E-10	4.80E-03	7.40E-10	8.14E-02	2.06E-08
Th-230	1.31E-02	1.30E+01	5.50E-04	8.50E-11	3.30E-01	5.10E-08	1.55E+02	2.39E-05
Th-232	1.29E-02	2.70E-01	2.70E-03	4.20E-10	1.60E+00	2.50E-07	1.56E+01	2.44E-06
U-234	2.21E-02	6.20E+00	2.80E-04	4.30E-11	1.30E-01	2.00E-08	2.91E+01	4.47E-06
U-238	2.21E-02	6.00E+00	2.50E-04	3.90E-11	1.20E-01	1.90E-08	2.60E+01	4.11E-06
U-235	2.21E-02	3.00E-01	2.70E-04	4.20E-11	1.20E-01	1.90E-08	1.31E+00	2.08E-07
TOTAL							2.71E+02	4.39E-05

P1c

POP. - DOWNWIND EXPOSURE TO RESUSPENDED PARTICULATES

Phosphate Fertilizer

G= 1.00E+03

G1= 8.00E+03

G2= 3.15E+05

G3= 4.50E+02

S= 5.82E-06

PR(fatal cancers) = G * S * C * [(G1*RFInh) + (G2*RFInh) + (G3*Uf*RFInh)]

PD(person mrem) = G * S * C * [(G1*DFInh) + (G2*DFInh) + (G3*Uf*DFInh)]

Nuclide	Uf	C	DFInh	RFInh	DFInh	RFInh	PD	PR
Po-210	1.31E-02	1.80E-03	1.90E-03	2.90E-10	9.40E-03	1.50E-09	7.88E-04	1.26E-10
Pb-210	1.31E-02	1.80E-03	5.40E-03	8.40E-10	1.40E-02	2.20E-09	1.17E-03	1.85E-10
Ra-226	1.31E-02	2.50E-03	1.30E-03	2.00E-10	8.60E-03	1.30E-09	1.77E-03	4.49E-10
Th-228	1.29E-02	3.40E-04	4.00E-04	6.20E-11	3.40E-01	5.30E-08	5.59E-03	9.20E-10
Ra-228	1.29E-02	3.40E-04	1.40E-03	2.20E-10	4.80E-03	7.40E-10	1.32E-04	3.35E-11
Th-230	1.31E-02	1.60E-02	5.50E-04	8.50E-11	3.30E-01	5.10E-08	2.46E-01	3.80E-08
Th-232	1.29E-02	3.10E-04	2.70E-03	4.20E-10	1.60E+00	2.50E-07	2.31E-02	3.61E-09
U-234	2.21E-02	1.70E-02	2.80E-04	4.30E-11	1.30E-01	2.00E-08	1.03E-01	1.58E-08
U-238	2.21E-02	1.70E-02	2.50E-04	3.90E-11	1.20E-01	1.90E-08	9.50E-02	1.50E-08
U-235	2.21E-02	8.60E-04	2.70E-04	4.20E-11	1.20E-01	1.90E-08	4.83E-03	7.71E-10
TOTAL							4.81E-01	7.50E-08

P1d

POP. - DOWNWIND EXPOSURE TO RESUSPENDED PARTICULATES

for: Coal Ash

G= 1.00E+03

G1= 8.00E+03

G2= 3.15E+05

G3= 4.50E+02

S= 9.83E-07

PR(fatal cancers) = G * S * C * [(G1*RFInh) + (G2*RFG) + (G3*Uf*RFing)]

PD(person mrem) = G * S * C * [(G1*DFInh) + (G2*DFG) + (G3*Uf*DFing)]

Nuclide	Uf	C	DFing	RFing	DFInh	RFInh	PD	PR
Po-210	1.31E-02	7.00E+00	1.90E-03	2.90E-10	9.40E-03	1.50E-09	5.18E-01	8.26E-08
Pb-210	1.31E-02	6.80E+00	5.40E-03	8.40E-10	1.40E-02	2.20E-09	7.49E-01	1.18E-07
Ra-226	1.31E-02	3.70E+00	1.30E-03	2.00E-10	8.60E-03	1.30E-09	4.42E-01	1.12E-07
Th-228	1.29E-02	3.20E+00	4.00E-04	6.20E-11	3.40E-01	5.30E-08	8.89E+00	1.46E-06
Ra-228	1.29E-02	1.80E+00	1.40E-03	2.20E-10	4.80E-03	7.40E-10	1.18E-01	3.00E-08
Th-230	1.31E-02	2.30E+00	5.50E-04	8.50E-11	3.30E-01	5.10E-08	5.97E+00	9.22E-07
Th-232	1.29E-02	2.10E+00	2.70E-03	4.20E-10	1.60E+00	2.50E-07	2.64E+01	4.13E-06
U-234	2.21E-02	3.30E+00	2.80E-04	4.30E-11	1.30E-01	2.00E-08	3.37E+00	5.19E-07
U-238	2.21E-02	3.30E+00	2.50E-04	3.90E-11	1.20E-01	1.90E-08	3.11E+00	4.93E-07
U-235	2.21E-02	1.60E-01	2.70E-04	4.20E-11	1.20E-01	1.90E-08	1.52E-01	2.42E-08
TOTAL							4.97E+01	7.89E-06

P10

POP. - DOWNWIND EXPOSURE TO RESUSPENDED PARTICULATES
for: Water Treat Sludge (Fertilizer)

$$G = 1.00E+03$$

$$G1 = 8.00E+03$$

$$G2 = 3.15E+05$$

$$G3 = 4.50E+02$$

$$S = 6.14E-06$$

$$PR(\text{fatal cancers}) = G \cdot S \cdot C \cdot [(G1 \cdot RFinh) + (G2 \cdot RFG) + (G3 \cdot Uf \cdot RFinh)]$$

$$PD(\text{person mrem}) = G \cdot S \cdot C \cdot [(G1 \cdot DFinh) + (G2 \cdot DFG) + (G3 \cdot Uf \cdot DFinh)]$$

Nuclide	Uf	C	DFinh	RFinh	DFinh	RFinh	PD	PR
Po-210	1.31E-02	4.00E-01	1.90E-03	2.90E-10	9.40E-03	1.50E-09	1.85E-01	2.95E-08
Pb-210	1.31E-02	4.00E-01	5.40E-03	8.40E-10	1.40E-02	2.20E-09	2.75E-01	4.33E-08
Ra-226	1.31E-02	6.40E-01	1.30E-03	2.00E-10	8.60E-03	1.30E-09	4.77E-01	1.21E-07
Th-228	1.29E-02	8.00E-03	4.00E-04	6.20E-11	3.40E-01	5.30E-08	1.39E-01	2.28E-08
Ra-228	1.29E-02	8.00E-01	1.40E-03	2.20E-10	4.80E-03	7.40E-10	3.29E-01	8.32E-08
Th-230	1.31E-02	8.00E-03	5.50E-04	8.50E-11	3.30E-01	5.10E-08	1.30E-01	2.00E-08
Th-232	1.29E-02	8.00E-03	2.70E-03	4.20E-10	1.60E+00	2.50E-07	6.29E-01	9.82E-08
U-234	2.21E-02	1.60E-01	2.80E-04	4.30E-11	1.30E-01	2.00E-08	1.02E+00	1.57E-07
U-238	2.21E-02	1.60E-01	2.50E-04	3.90E-11	1.20E-01	1.90E-08	9.43E-01	1.49E-07
U-235	2.21E-02	1.20E-03	2.70E-04	4.20E-11	1.20E-01	1.90E-08	7.11E-03	1.14E-09
TOTAL							4.13E+00	7.26E-07

P11

POP. - DOWNWIND EXPOSURE TO RESUSPENDED PARTICULATES
for: Water Treat Sludge (Landfill)

G= 1.00E+03

G1= 8.00E+03

G2= 3.15E+05

G3= 4.50E+02

S= 1.25E-06

PR(fatal cancers) = G * S * C * [(G1*RFInh) + (G2*RFG) + (G3*U1*RFInh)]

PD(person mrem) = G * S * C * [(G1*DFInh) + (G2*DFG) + (G3*U1*DFInh)]

Nuclide	U1	C	DFInh	RFInh	DFInh	RFInh	PD	PR
Po-210	1.31E-02	1.50E-01	1.90E-03	2.90E-10	9.40E-03	1.50E-09	1.41E-02	2.25E-09
Pb-210	1.31E-02	1.50E-01	5.40E-03	8.40E-10	1.40E-02	2.20E-09	2.10E-02	3.31E-09
Ra-226	1.31E-02	2.40E-01	1.30E-03	2.00E-10	8.60E-03	1.30E-09	3.64E-02	9.26E-09
Th-228	1.29E-02	3.00E-03	4.00E-04	6.20E-11	3.40E-01	5.30E-08	1.06E-02	1.74E-09
Ra-228	1.29E-02	3.00E-01	1.40E-03	2.20E-10	4.80E-03	7.40E-10	2.51E-02	6.35E-09
Th-230	1.31E-02	3.00E-03	5.50E-04	8.50E-11	3.30E-01	5.10E-08	9.90E-03	1.53E-09
Th-232	1.29E-02	3.00E-03	2.70E-03	4.20E-10	1.60E+00	2.50E-07	4.80E-02	7.50E-09
U-234	2.21E-02	6.00E-02	2.80E-04	4.30E-11	1.30E-01	2.00E-08	7.80E-02	1.20E-08
U-238	2.21E-02	6.00E-02	2.50E-04	3.90E-11	1.20E-01	1.90E-08	7.20E-02	1.14E-08
U-235	2.21E-02	5.00E-04	2.70E-04	4.20E-11	1.20E-01	1.90E-08	6.03E-04	9.63E-11
TOTAL							3.16E-01	5.54E-08

P1g

POP. - DOWNWIND EXPOSURE TO RESUSPENDED PARTICULATES
for: Mineral Processing Waste

G= 1.00E+03

G1= 8.00E+03

G2= 3.15E+05

G3= 4.50E+02

S= 5.23E-07

PR(fatal cancers) = G * S * C * [(G1*RFInh) + (G2*RFG) + (G3*Uf*RFIng)]

PD(person mrem) = G * S * C * [(G1*DFInh) + (G2*DFG) + (G3*Uf*DFIng)]

Nuclide	Uf	C	DFIng	RFIng	DFInh	RFInh	PD	PR
Po-210	1.31E-02	2.50E+01	1.90E-03	2.90E-10	9.40E-03	1.50E-09	9.83E-01	1.57E-07
Pb-210	1.31E-02	2.50E+01	5.40E-03	8.40E-10	1.40E-02	2.20E-09	1.47E+00	2.31E-07
Ra-226	1.31E-02	3.50E+01	1.30E-03	2.00E-10	8.60E-03	1.30E-09	2.22E+00	5.65E-07
Th-228	1.29E-02	1.00E+01	4.00E-04	6.20E-11	3.40E-01	5.30E-08	1.48E+01	2.43E-06
Ra-228	1.29E-02	1.00E+01	1.40E-03	2.20E-10	4.80E-03	7.40E-10	3.50E-01	8.86E-08
Th-230	1.31E-02	3.50E+01	5.50E-04	8.50E-11	3.30E-01	5.10E-08	4.83E+01	7.47E-06
Th-232	1.29E-02	1.00E+01	2.70E-03	4.20E-10	1.60E+00	2.50E-07	6.69E+01	1.05E-05
U-234	2.21E-02	3.50E+01	2.80E-04	4.30E-11	1.30E-01	2.00E-08	1.90E+01	2.93E-06
U-238	2.21E-02	3.50E+01	2.50E-04	3.90E-11	1.20E-01	1.90E-08	1.76E+01	2.78E-06
U-235	2.21E-02	1.80E+00	2.70E-04	4.20E-11	1.20E-01	1.90E-08	9.09E-01	1.45E-07
TOTAL							1.73E+02	2.73E-05

P1h

POP. - DOWNWIND EXPOSURE TO RESUSPENDED PARTICULATES
for: Oil & Gas Scale/ Sludge

G= 1.00E+03

G1= 8.00E+03

G2= 3.15E+05

G3= 4.50E+02

S= 2.72E-08

PR(fatal cancers) = G * S * C * [(G1*RFInh) + (G2*RFInh) + (G3*Uf*RFInh)]

PD(person mrem) = G * S * C * [(G1*DFInh) + (G2*DFInh) + (G3*Uf*DFInh)]

Nuclide	Uf	C	DFInh	RFInh	DFInh	RFInh	PD	PR
Po-210	1.31E-02	1.55E+02	1.90E-03	2.90E-10	9.40E-03	1.50E-09	3.17E-01	5.06E-08
Pb-210	1.31E-02	1.55E+02	5.40E-03	8.40E-10	1.40E-02	2.20E-09	4.73E-01	7.44E-08
Ra-226	1.31E-02	1.55E+02	1.30E-03	2.00E-10	8.60E-03	1.30E-09	5.12E-01	1.30E-07
Th-228	1.29E-02	5.50E+01	4.00E-04	6.20E-11	3.40E-01	5.30E-08	4.23E+00	6.96E-07
Ra-228	1.29E-02	5.50E+01	1.40E-03	2.20E-10	4.80E-03	7.40E-10	1.00E-01	2.54E-08
Th-230	1.31E-02	--	--	--	--	--	--	--
Th-232	1.29E-02	--	--	--	--	--	--	--
U-234	2.21E-02	--	--	--	--	--	--	--
U-238	2.21E-02	--	--	--	--	--	--	--
U-235	2.21E-02	--	--	--	--	--	--	--
TOTAL							5.63E+00	9.76E-07

P11

POP. - DOWNWIND EXPOSURE TO RESUSPENDED PARTICULATES
for: Geothermal Waste

G= 1.00E+03

G1= 8.00E+03

G2= 3.15E+05

G3= 4.50E+02

S= 5.05E-08

PR(fatal cancers) = G * S * C * [(G1*RFInh) + (G2*RFInh) + (G3*UI*RFInh)]

PD(person mrem) = G * S * C * [(G1*DFInh) + (G2*DFInh) + (G3*UI*DFInh)]

Nuclide	UI	C	DFInh	RFInh	DFInh	RFInh	PD	PR
Po-210	1.31E-02	1.10E+02	1.90E-03	2.90E-10	9.40E-03	1.50E-09	4.18E-01	6.67E-08
Pb-210	1.31E-02	1.10E+02	5.40E-03	8.40E-10	1.40E-02	2.20E-09	6.23E-01	9.80E-08
Ra-226	1.31E-02	1.60E+02	1.30E-03	2.00E-10	8.60E-03	1.30E-09	9.81E-01	2.49E-07
Th-228	1.29E-02	3.00E+01	4.00E-04	6.20E-11	3.40E-01	5.30E-08	4.28E+00	7.04E-07
Ra-228	1.29E-02	1.10E+02	1.40E-03	2.20E-10	4.80E-03	7.40E-10	3.72E-01	9.41E-08
Th-230	1.31E-02	--	--	--	--	--	--	--
Th-232	1.29E-02	--	--	--	--	--	--	--
U-234	2.21E-02	--	--	--	--	--	--	--
U-238	2.21E-02	--	--	--	--	--	--	--
U-235	2.21E-02	--	--	--	--	--	--	--
TOTAL							6.67E+00	1.21E-06

P2a

POPULATION - DOWNWIND EXPOSURE TO RADON
for: Uranium Overburden

G= 2.53E+00

S= 3.09E+03

DFr= 4.90E-07

$$\text{PR(fatal cancers)} = G \cdot S \cdot \text{DFr}$$

Nuclide	PR
Ra-226	3.83E-03
TOTAL	3.83E-03

P2b

POPULATION - DOWNWIND EXPOSURE TO RADON
for: Phosphate Waste

G= 2.53E+00
S= 1.28E+04
DFr= 4.90E-07

$$PR(\text{fatal cancers}) = G \cdot S \cdot DFr$$

Nuclide	PR
Ra-226	1.59E-02
TOTAL	1.59E-02

P2c

POPULATION - DOWNWIND EXPOSURE TO RADON
for: Phosphate Fertilizer

G= 2.53E+00
S= 1.28E-01
DFr= 4.90E-07

$$\text{PR(fatal cancers)} = G \cdot S \cdot \text{DFr}$$

Nuclide	PR
Ra-226	1.59E-07
TOTAL	1.59E-07

P2d

POPULATION - DOWNWIND EXPOSURE TO RADON
for: Coal Ash

G= 2.53E+00
S= 6.31E+01
DFr= 4.90E-07

$$PR(\text{fatal cancers}) = G \cdot S \cdot DFr$$

Nuclide	PR
Ra-226	7.82E-05
TOTAL	7.82E-05

P2e

POPULATION - DOWNWIND EXPOSURE TO RADON
for: Water Treat Sludge (Fertilizer)

$$G= 2.53E+00$$

$$S= 3.76E+01$$

$$DFr= 4.90E-07$$

$$PR(\text{fatal cancers}) = G \cdot S \cdot DFr$$

Nuclide	PR
Ra-226	4.66E-05
TOTAL	4.66E-05

P21

POPULATION - DOWNWIND EXPOSURE TO RADON
for: Water Treatment Sludge (Landfill)

$G = 2.53E+00$
 $S = 9.91E+00$
 $DFr = 4.90E-07$

$$PR(\text{fatal cancers}) = G \cdot S \cdot DFr$$

Nuclide	PR
Ra-226	1.23E-05
TOTAL	1.23E-05

P2g

POPULATION - DOWNWIND EXPOSURE TO RADON
for: Mineral Processing Waste

G= 2.53E+00
S= 1.35E+03
DFr= 4.90E-07

$$\text{PR(fatal cancers)} = G \cdot S \cdot \text{DFr}$$

Nuclide	PR
Ra-226	1.67E-03
TOTAL	1.67E-03

P2h

POPULATION - DOWNWIND EXPOSURE TO RADON
for: Oil & Gas Scale/ Sludge

G= 2.53E+00
S= 5.48E+02
DFr= 4.90E-07

$$PR(\text{fatal cancers}) = G \cdot S \cdot DFr$$

Nuclide	PR
Ra-226	6.79E-04
TOTAL	6.79E-04

P21

POPULATION - DOWNWIND EXPOSURE TO RADON
for: Geothermal Waste

G= 2.53E+00
S= 4.45E+03
DFr= 4.90E-07

$$\text{PR(fatal cancers)} = G \cdot S \cdot \text{DFr}$$

Nuclide	PR
Ra-226	5.52E-03
TOTAL	5.52E-03

P3a

**POPULATION - INGESTION OF RIVER WATER
CONTAMINATED VIA THE GROUNDWATER PATHWAY
for: Uranium Overburden**

G= 2.00E-07

S= 3.27E+15

1-exp= 3.40E-05

PD(mrem) = (G * S * C * Uw * DFing * (1-exp)) / R

PR(fatal cancers) = (G * S * C * Uw * RFing * (1-exp)) / R

Nuclide	C	DFing	RFing	R	Uw	PD	PR
Po-210	1.66E+01	1.90E-03	2.90E-10	2.74E+02	9.43E-01	2.41E+00	3.68E-07
Pb-210	1.66E+01	5.40E-03	8.40E-10	4.92E+02	9.43E-01	3.82E+00	5.94E-07
Ra-226	2.37E+01	1.30E-03	2.00E-10	2.46E+02	9.43E-01	2.63E+00	4.04E-07
Th-228	1.00E+00	4.00E-04	6.20E-11	8.18E+04	9.39E-01	1.02E-04	1.58E-11
Ra-228	1.00E+00	1.40E-03	2.20E-10	2.46E+02	9.39E-01	1.19E-01	1.87E-08
Th-230	2.37E+01	5.50E-04	8.50E-11	8.18E+04	9.43E-01	3.34E-03	5.16E-10
Th-232	1.00E+00	2.70E-03	4.20E-10	8.18E+04	9.39E-01	6.89E-04	1.07E-10
U-234	2.37E+01	2.80E-04	4.30E-11	2.46E+02	8.76E-01	5.25E-01	8.07E-08
U-238	2.37E+01	2.50E-04	3.90E-11	2.46E+02	8.76E-01	4.69E-01	7.32E-08
U-235	1.20E+00	2.70E-04	4.20E-11	2.46E+02	8.76E-01	2.57E-02	3.99E-09
TOTAL						1.00E+01	1.54E-06

P3b

**POPULATION - INGESTION OF RIVER WATER
CONTAMINATED VIA THE GROUNDWATER PATHWAY
for: Phosphate Waste**

G= 2.00E-07

S= 6.71E+15

1-exp= 3.50E-02

PD(mrem) = (G * S * C * Uw * DFing * (1-exp)) / R

PR(fatal cancers) = (G * S * C * Uw * RFing * (1-exp)) / R

Nuclide	C	DFing	RFing	R	Uw	PD	PR
Po-210	2.64E+01	1.90E-03	2.90E-10	2.73E+03	9.43E-01	8.14E+02	1.24E-04
Pb-210	2.64E+01	5.40E-03	8.40E-10	4.91E+03	9.43E-01	1.29E+03	2.00E-04
Ra-226	3.30E+01	1.30E-03	2.00E-10	2.45E+03	9.43E-01	7.76E+02	1.19E-04
Th-228	2.70E-01	4.00E-04	6.20E-11	8.18E+05	9.39E-01	5.82E-03	9.03E-10
Ra-228	2.70E-01	1.40E-03	2.20E-10	2.45E+03	9.39E-01	6.80E+00	1.07E-06
Th-230	1.30E+01	5.50E-04	8.50E-11	8.18E+05	9.43E-01	3.87E-01	5.98E-08
Th-232	2.70E-01	2.70E-03	4.20E-10	8.18E+05	9.39E-01	3.93E-02	6.11E-09
U-234	6.20E+00	2.80E-04	4.30E-11	2.45E+03	8.76E-01	2.92E+01	4.48E-06
U-238	6.00E+00	2.50E-04	3.90E-11	2.45E+03	8.76E-01	2.52E+01	3.93E-06
U-235	3.00E-01	2.70E-04	4.20E-11	2.45E+03	8.76E-01	1.36E+00	2.12E-07
TOTAL						2.94E+03	4.53E-04

P3c

**POPULATION - INGESTION OF RIVER WATER
CONTAMINATED VIA THE GROUNDWATER PATHWAY
Phosphate Fertilizer**

G= 2.00E-07

S= 6.52E+13

1-exp= 8.80E-03

PD(mrem) = (G * S * C * Uw * DFing * (1-exp)) / R

PR(fatal cancers) = (G * S * C * Uw * RFing * (1-exp)) / R

Nuclide	C	DFing	RFing	R	Uw	PD	PR
Po-210	1.80E-03	1.90E-03	2.90E-10	2.73E+03	9.43E-01	1.36E-04	2.07E-11
Pb-210	1.80E-03	5.40E-03	8.40E-10	4.91E+03	9.43E-01	2.14E-04	3.33E-11
Ra-226	2.50E-03	1.30E-03	2.00E-10	2.45E+03	9.43E-01	1.44E-04	2.21E-11
Th-228	3.40E-04	4.00E-04	6.20E-11	8.18E+05	9.39E-01	1.79E-08	2.78E-15
Ra-228	3.40E-04	1.40E-03	2.20E-10	2.45E+03	9.39E-01	2.09E-05	3.29E-12
Th-230	1.60E-02	5.50E-04	8.50E-11	8.18E+05	9.43E-01	1.16E-06	1.80E-13
Th-232	3.10E-04	2.70E-03	4.20E-10	8.18E+05	9.39E-01	1.10E-07	1.72E-14
U-234	1.70E-02	2.80E-04	4.30E-11	2.45E+03	8.76E-01	1.95E-04	3.00E-11
U-238	1.70E-02	2.50E-04	3.90E-11	2.45E+03	8.76E-01	1.74E-04	2.72E-11
U-235	8.60E-04	2.70E-04	4.20E-11	2.45E+03	8.76E-01	9.53E-06	1.48E-12
TOTAL						8.95E-04	1.38E-10

P3d

**POPULATION - INGESTION OF RIVER WATER
CONTAMINATED VIA THE GROUNDWATER PATHWAY
for: Coal Ash**

G= 2.00E-07

S= 2.55E+15

1-exp= 6.70E-02

PD(mrem) = (G * S * C * Uw * DFing * (1-exp)) / R

PR(fatal cancers) = (G * S * C * Uw * RFing * (1-exp)) / R

Nuclide	C	DFing	RFing	R	Uw	PD	PR
Po-210	7.00E+00	1.90E-03	2.90E-10	5.46E+02	9.43E-01	7.85E+02	1.20E-04
Pb-210	6.80E+00	5.40E-03	8.40E-10	5.46E+02	9.43E-01	2.17E+03	3.37E-04
Ra-226	3.70E+00	1.30E-03	2.00E-10	4.10E+02	9.43E-01	3.78E+02	5.82E-05
Th-228	3.20E+00	4.00E-04	6.20E-11	1.64E+04	9.39E-01	2.50E+00	3.88E-07
Ra-228	1.80E+00	1.40E-03	2.20E-10	4.10E+02	9.39E-01	1.97E+02	3.10E-05
Th-230	2.30E+00	5.50E-04	8.50E-11	1.64E+04	9.43E-01	2.49E+00	3.84E-07
Th-232	2.10E+00	2.70E-03	4.20E-10	1.64E+04	9.39E-01	1.11E+01	1.73E-06
U-234	3.30E+00	2.80E-04	4.30E-11	2.74E+02	8.76E-01	1.01E+02	1.55E-05
U-238	3.30E+00	2.50E-04	3.90E-11	2.74E+02	8.76E-01	9.01E+01	1.41E-05
U-235	1.60E-01	2.70E-04	4.20E-11	2.74E+02	8.76E-01	4.72E+00	7.34E-07
TOTAL						3.74E+03	5.79E-04

P3e

**POPULATION - INGESTION OF RIVER WATER
CONTAMINATED VIA THE GROUNDWATER PATHWAY
for: Water Treat Sludge (Fertilizer)**

$$G = 2.00E-07$$

$$S = 6.52E+13$$

$$1-\exp = 8.70E-03$$

$$PD(mrem) = (G \cdot S \cdot C \cdot U_w \cdot DFing \cdot (1-\exp)) / R$$

$$PR(fatal\ cancers) = (G \cdot S \cdot C \cdot U_w \cdot RFing \cdot (1-\exp)) / R$$

Nuclide	C	DFing	RFing	R	Uw	PD	PR
Po-210	4.00E-01	1.90E-03	2.90E-10	2.73E+03	9.43E-01	2.98E-02	4.55E-09
Pb-210	4.00E-01	5.40E-03	8.40E-10	4.91E+03	9.43E-01	4.71E-02	7.32E-09
Ra-226	6.40E-01	1.30E-03	2.00E-10	2.45E+03	9.43E-01	3.63E-02	5.59E-09
Th-228	8.00E-03	4.00E-04	6.20E-11	8.18E+05	9.39E-01	4.17E-07	6.46E-14
Ra-228	8.00E-01	1.40E-03	2.20E-10	2.45E+03	9.39E-01	4.87E-02	7.65E-09
Th-230	8.00E-03	5.50E-04	8.50E-11	8.18E+05	9.43E-01	5.75E-07	8.89E-14
Th-232	8.00E-03	2.70E-03	4.20E-10	8.18E+05	9.39E-01	2.81E-06	4.38E-13
U-234	1.60E-01	2.80E-04	4.30E-11	2.45E+03	8.76E-01	1.82E-03	2.79E-10
U-238	1.60E-01	2.50E-04	3.90E-11	2.45E+03	8.76E-01	1.62E-03	2.53E-10
U-235	1.20E-03	2.70E-04	4.20E-11	2.45E+03	8.76E-01	1.31E-05	2.04E-12
TOTAL						1.65E-01	2.56E-08

P31

**POPULATION - INGESTION OF RIVER WATER
CONTAMINATED VIA THE GROUNDWATER PATHWAY
for: Water Treat Sludge (Landfill)**

$$G = 2.00E-07$$

$$S = 2.93E+14$$

$$1 - \exp = 2.20E-04$$

$$PD(mrem) = (G \cdot S \cdot C \cdot U_w \cdot DFing \cdot (1 - \exp)) / R$$

$$PR(fatal\ cancers) = (G \cdot S \cdot C \cdot U_w \cdot RFing \cdot (1 - \exp)) / R$$

Nuclide	C	DFing	RFing	R	Uw	PD	PR
Po-210	1.50E-01	1.90E-03	2.90E-10	2.73E+03	9.43E-01	1.27E-03	1.94E-10
Pb-210	1.50E-01	5.40E-03	8.40E-10	4.91E+03	9.43E-01	2.01E-03	3.12E-10
Ra-226	2.40E-01	1.30E-03	2.00E-10	2.45E+03	9.43E-01	1.55E-03	2.38E-10
Th-228	3.00E-03	4.00E-04	6.20E-11	8.18E+05	9.39E-01	1.78E-08	2.75E-15
Ra-228	3.00E-01	1.40E-03	2.20E-10	2.45E+03	9.39E-01	2.08E-03	3.26E-10
Th-230	3.00E-03	5.50E-04	8.50E-11	8.18E+05	9.43E-01	2.45E-08	3.79E-15
Th-232	3.00E-03	2.70E-03	4.20E-10	8.18E+05	9.39E-01	1.20E-07	1.86E-14
U-234	6.00E-02	2.80E-04	4.30E-11	2.45E+03	8.76E-01	7.74E-05	1.19E-11
U-238	6.00E-02	2.50E-04	3.90E-11	2.45E+03	8.76E-01	6.91E-05	1.08E-11
U-235	5.00E-04	2.70E-04	4.20E-11	2.45E+03	8.76E-01	6.22E-07	9.68E-14
TOTAL						7.05E-03	1.09E-09

P3g

**POPULATION - INGESTION OF RIVER WATER
CONTAMINATED VIA THE GROUNDWATER PATHWAY
for: Mineral Processing Waste**

$$G = 2.00E-07$$

$$S = 2.14E+15$$

$$1 - \exp = 2.00E-08$$

$$PD(mrem) = (G \cdot S \cdot C \cdot U_w \cdot DFing \cdot (1 - \exp)) / R$$

$$PR(fatal\ cancers) = (G \cdot S \cdot C \cdot U_w \cdot RFing \cdot (1 - \exp)) / R$$

Nuclide	C	DFing	RFing	R	Uw	PD	PR
Po-210	2.50E+01	1.90E-03	2.90E-10	2.74E+02	9.43E-01	1.40E-01	2.14E-08
Pb-210	2.50E+01	5.40E-03	8.40E-10	4.92E+02	9.43E-01	2.21E-01	3.45E-08
Ra-226	3.50E+01	1.30E-03	2.00E-10	2.46E+02	9.43E-01	1.49E-01	2.30E-08
Th-228	1.00E+01	4.00E-04	6.20E-11	8.18E+04	9.39E-01	3.93E-05	6.09E-12
Ra-228	1.00E+01	1.40E-03	2.20E-10	2.46E+02	9.39E-01	4.57E-02	7.19E-09
Th-230	3.50E+01	5.50E-04	8.50E-11	8.18E+04	9.43E-01	1.90E-04	2.94E-11
Th-232	1.00E+01	2.70E-03	4.20E-10	8.18E+04	9.39E-01	2.65E-04	4.13E-11
U-234	3.50E+01	2.80E-04	4.30E-11	2.46E+02	8.76E-01	2.99E-02	4.59E-09
U-238	3.50E+01	2.50E-04	3.90E-11	2.46E+03	8.76E-01	2.67E-03	4.16E-10
U-235	1.80E+00	2.70E-04	4.20E-11	2.46E+02	8.76E-01	1.48E-03	2.30E-10
TOTAL						5.91E-01	9.13E-08

P3h

**POPULATION - INGESTION OF RIVER WATER
CONTAMINATED VIA THE GROUNDWATER PATHWAY
for: Oil & Gas Scale/ Sludge**

G= 2.00E-07

S= 2.28E+14

1-exp= 3.00E-03

PD(mrem) = (G * S * C * Uw * DFing * (1-exp)) / R

PR(fatal cancers) = (G * S * C * Uw * RFing * (1-exp)) / R

Nuclide	C	DFing	RFing	R	Uw	PD	PR
Po-210	1.55E+02	1.90E-03	2.90E-10	5.46E+02	9.43E-01	6.96E+01	1.06E-05
Pb-210	1.55E+02	5.40E-03	8.40E-10	5.46E+02	9.43E-01	1.98E+02	3.08E-05
Ra-226	1.55E+02	1.30E-03	2.00E-10	1.36E+04	9.43E-01	1.91E+00	2.94E-07
Th-228	5.50E+01	4.00E-04	6.20E-11	1.36E+04	9.39E-01	2.08E-01	3.22E-08
Ra-228	5.50E+01	1.40E-03	2.20E-10	1.36E+04	9.39E-01	7.27E-01	1.14E-07
Th-230	--	--	--	--	--	--	--
Th-232	--	--	--	--	--	--	--
U-234	--	--	--	--	--	--	--
U-238	--	--	--	--	--	--	--
U-235	--	--	--	--	--	--	--
TOTAL						2.70E+02	4.18E-05

P31

**POPULATION - INGESTION OF RIVER WATER
CONTAMINATED VIA THE GROUNDWATER PATHWAY
for: Geothermal Waste**

G= 2.00E-07

S= 4.62E+14

-exp= 5.80E-05

PD(rem) = (G * S * C * Uw * DFing * (1-exp)) / R

PR(tal cancers) = (G * S * C * Uw * RFing * (1-exp)) / R

Nuclide	C	DFing	RFing	R	Uw	PD	PR
Po-210	1.1 E+02	1.90E-03	2.90E-10	2.74E+02	9.43E-01	3.85E+00	5.88E-07
Pb-210	1.1 E+02	5.40E-03	8.40E-10	4.92E+02	9.43E-01	6.10E+00	9.49E-07
Ra-226	1.6 E+02	1.30E-03	2.00E-10	2.46E+02	9.43E-01	4.27E+00	6.57E-07
Th-228	3.0 E+01	4.00E-04	6.20E-11	8.18E+04	9.39E-01	7.38E-04	1.14E-10
Ra-228	1.1 E+02	1.40E-03	2.20E-10	2.46E+02	9.39E-01	3.15E+00	4.95E-07
Th-230	--	--	--	--	--	--	--
Th-232	--	--	--	--	--	--	--
U-234	--	--	--	--	--	--	--
U-238	--	--	--	--	--	--	--
U-235	--	--	--	--	--	--	--
TOTAL						1.74E+01	2.69E-06

P4a

**POPULATION - INGESTION OF RIVER
WATER CONTAMINATED BY SURFACE RUNOFF
for: Uranium Overburden
G= 3.50E-09
S= 7.06E+16**

$$PD(mrem) = (G \cdot S \cdot C \cdot U_w \cdot DFing) / R$$

$$PR(fatal\ cancers) = (G \cdot S \cdot C \cdot U_w \cdot RFing) / R$$

Nuclide	C	DFing	RFing	R	Uw	PD	PR
Po-210	1.66E+01	1.90E-03	2.90E-10	2.74E+02	9.43E-01	2.68E+04	4.09E-03
Pb-210	1.66E+01	5.40E-03	8.40E-10	4.92E+02	9.43E-01	4.25E+04	6.60E-03
Ra-226	2.37E+01	1.30E-03	2.00E-10	2.46E+02	9.43E-01	2.92E+04	4.49E-03
Th-228	1.00E+00	4.00E-04	6.20E-11	8.18E+04	9.39E-01	1.13E+00	1.76E-07
Ra-228	1.00E+00	1.40E-03	2.20E-10	2.46E+02	9.39E-01	1.32E+03	2.08E-04
Th-230	2.37E+01	5.50E-04	8.50E-11	8.18E+04	9.43E-01	3.71E+01	5.74E-06
Th-232	1.00E+00	2.70E-03	4.20E-10	8.18E+04	9.39E-01	7.66E+00	1.19E-06
U-234	2.37E+01	2.80E-04	4.30E-11	2.46E+02	8.76E-01	5.84E+03	8.97E-04
U-238	2.37E+01	2.50E-04	3.90E-11	2.46E+02	8.76E-01	5.21E+03	8.13E-04
U-235	1.20E+00	2.70E-04	4.20E-11	2.46E+02	8.76E-01	2.85E+02	4.43E-05
TOTAL						1.11E+05	1.72E-02

P4b

**POPULATION - INGESTION OF RIVER
WATER CONTAMINATED BY SURFACE RUNOFF
for: Phosphate Waste
G= 3.50E-09
S= 1.03E+18**

$$PD(mrem) = (G \cdot S \cdot C \cdot U_w \cdot DFing) / R$$

$$PR(fatal\ cancers) = (G \cdot S \cdot C \cdot U_w \cdot RFing) / R$$

Nuclide	C	DFing	RFing	R	Uw	PD	PR
Po-210	2.64E+01	1.90E-03	2.90E-10	2.73E+03	9.43E-01	6.25E+04	9.53E-03
Pb-210	2.64E+01	5.40E-03	8.40E-10	4.91E+03	9.43E-01	9.87E+04	1.54E-02
Ra-226	3.30E+01	1.30E-03	2.00E-10	2.45E+03	9.43E-01	5.95E+04	9.16E-03
Th-228	2.70E-01	4.00E-04	6.20E-11	8.18E+05	9.39E-01	4.47E-01	6.93E-08
Ra-228	2.70E-01	1.40E-03	2.20E-10	2.45E+03	9.39E-01	5.22E+02	8.21E-05
Th-230	1.30E+01	5.50E-04	8.50E-11	8.18E+05	9.43E-01	2.97E+01	4.59E-06
Th-232	2.70E-01	2.70E-03	4.20E-10	8.18E+05	9.39E-01	3.02E+00	4.69E-07
U-234	6.20E+00	2.80E-04	4.30E-11	2.45E+03	8.76E-01	2.24E+03	3.44E-04
U-238	6.00E+00	2.50E-04	3.90E-11	2.45E+03	8.76E-01	1.93E+03	3.02E-04
U-235	3.00E-01	2.70E-04	4.20E-11	2.45E+03	8.76E-01	1.04E+02	1.62E-05
TOTAL						2.26E+05	3.48E-02

P4c

POPULATION - INGESTION OF RIVER
WATER CONTAMINATED BY SURFACE RUNOFF
Phosphate Fertilizer
G= 3.50E-09
S= 2.32E+17

$$PD(mrem) = (G \cdot S \cdot C \cdot U_w \cdot DFing) / R$$

$$PR(fatal\ cancers) = (G \cdot S \cdot C \cdot U_w \cdot RFing) / R$$

Nuclide	C	DFing	RFing	R	Uw	PD	PR
Po-210	1.80E-03	1.90E-03	2.90E-10	2.73E+03	9.43E-01	9.59E-01	1.46E-07
Pb-210	1.80E-03	5.40E-03	8.40E-10	4.91E+03	9.43E-01	1.52E+00	2.36E-07
Ra-226	2.50E-03	1.30E-03	2.00E-10	2.45E+03	9.43E-01	1.02E+00	1.56E-07
Th-228	3.40E-04	4.00E-04	6.20E-11	8.18E+05	9.39E-01	1.27E-04	1.96E-11
Ra-228	3.40E-04	1.40E-03	2.20E-10	2.45E+03	9.39E-01	1.48E-01	2.33E-08
Th-230	1.60E-02	5.50E-04	8.50E-11	8.18E+05	9.43E-01	8.24E-03	1.27E-09
Th-232	3.10E-04	2.70E-03	4.20E-10	8.18E+05	9.39E-01	7.80E-04	1.21E-10
U-234	1.70E-02	2.80E-04	4.30E-11	2.45E+03	8.76E-01	1.38E+00	2.12E-07
U-238	1.70E-02	2.50E-04	3.90E-11	2.45E+03	8.76E-01	1.23E+00	1.92E-07
U-235	8.60E-04	2.70E-04	4.20E-11	2.45E+03	8.76E-01	6.74E-02	1.05E-08
TOTAL						6.33E+00	9.78E-07

P4d

POPULATION - INGESTION OF RIVER
WATER CONTAMINATED BY SURFACE RUNOFF
for: Coal Ash
G= 3.50E-09
S= 1.40E+17

$$PD(mrem) = (G \cdot S \cdot C \cdot Uw \cdot DFing) / R$$

$$PR(fatal\ cancers) = (G \cdot S \cdot C \cdot Uw \cdot RFing) / R$$

Nuclide	C	DFing	RFing	R	Uw	PD	PR
Po-210	7.00E+00	1.90E-03	2.90E-10	5.46E+02	9.43E-01	1.13E+04	1.72E-03
Pb-210	6.80E+00	5.40E-03	8.40E-10	5.46E+02	9.43E-01	3.11E+04	4.83E-03
Ra-226	3.70E+00	1.30E-03	2.00E-10	4.10E+02	9.43E-01	5.42E+03	8.34E-04
Th-228	3.20E+00	4.00E-04	6.20E-11	1.64E+04	9.39E-01	3.59E+01	5.57E-06
Ra-228	1.80E+00	1.40E-03	2.20E-10	4.10E+02	9.39E-01	2.83E+03	4.44E-04
Th-230	2.30E+00	5.50E-04	8.50E-11	1.64E+04	9.43E-01	3.56E+01	5.51E-06
Th-232	2.10E+00	2.70E-03	4.20E-10	1.64E+04	9.39E-01	1.59E+02	2.47E-05
U-234	3.30E+00	2.80E-04	4.30E-11	2.74E+02	8.76E-01	1.45E+03	2.22E-04
U-238	3.30E+00	2.50E-04	3.90E-11	2.74E+02	8.76E-01	1.29E+03	2.02E-04
U-235	1.60E-01	2.70E-04	4.20E-11	2.74E+02	8.76E-01	6.77E+01	1.05E-05
TOTAL						5.36E+04	8.30E-03

P4e

**POPULATION - INGESTION OF RIVER
WATER CONTAMINATED BY SURFACE RUNOFF**
for: Water Treat Sludge (Fertilizer)
G= 3.50E-09
S= 1.99E+17

$$PD(mrem) = (G \cdot S \cdot C \cdot U_w \cdot DFing) / R$$

$$PR(fatal\ cancers) = (G \cdot S \cdot C \cdot U_w \cdot RFing) / R$$

Nuclide	C	DFing	RFing	R	Uw	PD	PR
Po-210	4.00E-01	1.90E-03	2.90E-10	2.73E+03	9.43E-01	1.83E+02	79E-05
Pb-210	4.00E-01	5.40E-03	8.40E-10	4.91E+03	9.43E-01	2.89E+02	49E-05
Ra-226	6.40E-01	1.30E-03	2.00E-10	2.45E+03	9.43E-01	2.23E+02	43E-05
Th-228	8.00E-03	4.00E-04	6.20E-11	8.18E+05	9.39E-01	2.56E-03	97E-10
Ra-228	8.00E-01	1.40E-03	2.20E-10	2.45E+03	9.39E-01	2.99E+02	70E-05
Th-230	8.00E-03	5.50E-04	8.50E-11	8.18E+05	9.43E-01	3.53E-03	46E-10
Th-232	8.00E-03	2.70E-03	4.20E-10	8.18E+05	9.39E-01	1.73E-02	69E-09
U-234	1.60E-01	2.80E-04	4.30E-11	2.45E+03	8.76E-01	1.12E+01	71E-06
U-238	1.60E-01	2.50E-04	3.90E-11	2.45E+03	8.76E-01	9.96E+00	55E-06
U-235	1.20E-03	2.70E-04	4.20E-11	2.45E+03	8.76E-01	8.07E-02	26E-08
TOTAL						1.02E+03	57E-04

P41

**POPULATION - INGESTION OF RIVER
WATER CONTAMINATED BY SURFACE RUNOFF
for: Water Treat Sludge (Landfill)**
G= 3.50E-09
S= 2.65E+16

$$PD(mrem) = (G \cdot S \cdot C \cdot U_w \cdot DFing) / R$$

$$PR(fatal\ cancers) = (G \cdot S \cdot C \cdot U_w \cdot RFing) / R$$

Nuclide	C	DFing	RFing	R	Uw	PD	PR
Po-210	1.50E-01	1.90E-03	2.90E-10	2.73E+03	9.43E-01	9.13E+00	1.39E-06
Pb-210	1.50E-01	5.40E-03	8.40E-10	4.91E+03	9.43E-01	1.44E+01	2.24E-06
Ra-226	2.40E-01	1.30E-03	2.00E-10	2.45E+03	9.43E-01	1.11E+01	1.71E-06
Th-228	3.00E-03	4.00E-04	6.20E-11	8.18E+05	9.39E-01	1.28E-04	1.98E-11
Ra-228	3.00E-01	1.40E-03	2.20E-10	2.45E+03	9.39E-01	1.49E+01	2.35E-06
Th-230	3.00E-03	5.50E-04	8.50E-11	8.18E+05	9.43E-01	1.76E-04	2.73E-11
Th-232	3.00E-03	2.70E-03	4.20E-10	8.18E+05	9.39E-01	8.62E-04	1.34E-10
U-234	6.00E-02	2.80E-04	4.30E-11	2.45E+03	8.76E-01	5.57E-01	8.56E-08
U-238	6.00E-02	2.50E-04	3.90E-11	2.45E+03	8.76E-01	4.97E-01	7.76E-08
U-235	5.00E-04	2.70E-04	4.20E-11	2.45E+03	8.76E-01	4.48E-03	6.96E-10
TOTAL						5.07E+01	7.86E-06

P4g

**POPULATION - INGESTION OF RIVER
WATER CONTAMINATED BY SURFACE RUNOFF :
for: Mineral Processing Waste
G= 3.50E-09
S= 6.86E+15**

$$PD(mrem) = (G \cdot S \cdot C \cdot U_w \cdot DFing) / R$$

$$PR(fatal\ cancers) = (G \cdot S \cdot C \cdot U_w \cdot RFing) / R$$

Nuclide	C	DFing	RFing	R	Uw	PD	PR
Po-210	2.50E+01	1.90E-03	2.90E-10	2.74E+02	.43E-01	3.93E+03	5.99E-04
Pb-210	2.50E+01	5.40E-03	8.40E-10	4.92E+02	.43E-01	6.21E+03	9.66E-04
Ra-226	3.50E+01	1.30E-03	2.00E-10	2.46E+02	.43E-01	4.19E+03	6.44E-04
Th-228	1.00E+01	4.00E-04	6.20E-11	8.18E+04	.39E-01	1.10E+00	1.71E-07
Ra-228	1.00E+01	1.40E-03	2.20E-10	2.46E+02	.39E-01	1.28E+03	2.02E-04
Th-230	3.50E+01	5.50E-04	8.50E-11	8.18E+04	.43E-01	5.33E+00	8.23E-07
Th-232	1.00E+01	2.70E-03	4.20E-10	8.18E+04	.39E-01	7.44E+00	1.16E-06
U-234	3.50E+01	2.80E-04	4.30E-11	2.46E+02	.76E-01	8.38E+02	1.29E-04
U-238	3.50E+01	2.50E-04	3.90E-11	2.46E+03	.76E-01	7.48E+01	1.17E-05
U-235	1.80E+00	2.70E-04	4.20E-11	2.46E+02	.76E-01	4.16E+01	6.46E-06
					TOTAL	1.66E+04	2.56E-03

P4h

**POPULATION - INGESTION OF RIVER
WATER CONTAMINATED BY SURFACE RUNOFF
for: Oil & Gas Scale/ Sludge
G= 3.50E-09
S= 5.24E+15**

$$PD(mrem) = (G \cdot S \cdot C \cdot U_w \cdot DFing) / R$$

$$PR(fatal\ cancers) = (G \cdot S \cdot C \cdot U_w \cdot RFing) / R$$

Nuclide	C	DFing	RFing	R	Uw	PD	PR
Po-210	1.55E+02	1.90E-03	2.90E-10	5.46E+02	9.43E-01	9.33E+03	1.42E-03
Pb-210	1.55E+02	5.40E-03	8.40E-10	5.46E+02	9.43E-01	2.65E+04	4.12E-03
Ra-226	1.55E+02	1.30E-03	2.00E-10	1.36E+04	9.43E-01	2.56E+02	3.94E-05
Th-228	5.50E+01	4.00E-04	6.20E-11	1.36E+04	9.39E-01	2.79E+01	4.32E-06
Ra-228	5.50E+01	1.40E-03	2.20E-10	1.36E+04	9.39E-01	9.75E+01	1.53E-05
Th-230	--	--	--	--	--	--	--
Th-232	--	--	--	--	--	--	--
U-234	--	--	--	--	--	--	--
U-238	--	--	--	--	--	--	--
U-235	--	--	--	--	--	--	--
TOTAL						3.62E+04	5.61E-03

P41

**POPULATION - INGESTION OF RIVER
WATER CONTAMINATED BY SURFACE RUNOFF
for: Geothermal Waste
G= 3.50E-09
S= 4.32E+15**

$$PD(mrem) = (G \cdot S \cdot C \cdot U_w \cdot DFing) / R$$

$$PR(fatal\ cancers) = (G \cdot S \cdot C \cdot U_w \cdot RFing) / R$$

Nuclide	C	DFing	RFing	R	Uw	PD	PR
Po-210	1.10E+02	1.90E-03	2.90E-10	2.74E+02	9.43E-01	1.08E+04	1.66E-03
Pb-210	1.10E+02	5.40E-03	8.40E-10	4.92E+02	9.43E-01	1.72E+04	2.68E-03
Ra-226	1.60E+02	1.30E-03	2.00E-10	2.46E+02	9.43E-01	1.21E+04	1.85E-03
Th-228	3.00E+01	4.00E-04	6.20E-11	8.18E+04	9.39E-01	2.08E+00	3.23E-07
Ra-228	1.10E+02	1.40E-03	2.20E-10	2.46E+02	9.39E-01	8.89E+03	1.40E-03
Th-230	--	--	--	--	--	--	--
Th-232	--	--	--	--	--	--	--
U-234	--	--	--	--	--	--	--
U-238	--	--	--	--	--	--	--
U-235	--	--	--	--	--	--	--
TOTAL						4.90E+04	7.59E-03

P5c

**POPULATION - INGESTION OF FOODSTUFFS
GROWN ON REPEATEDLY FERTILIZED SOIL**

Phosphate Fertilizer

G= 4.93E+08

S= 1.00E+00

PD(mrem) = (G * S * C * Uf * DFing)

PR(fatal cancers) = (G * S * C * Uf * RFing)

Nuclide	C	DFing	RFing	Uf	PD	PR
Po-210	1.80E-03	1.90E-03	2.90E-10	1.31E-02	2.21E-01	3.37E-08
Pb-210	1.80E-03	5.40E-03	8.40E-10	1.31E-02	6.28E-01	9.76E-08
Ra-226	2.50E-03	1.30E-03	2.00E-10	1.31E-02	2.10E-01	3.23E-08
Th-228	3.40E-04	4.00E-04	6.20E-11	1.29E-02	8.65E-03	1.34E-09
Ra-228	3.40E-04	1.40E-03	2.20E-10	1.29E-02	3.03E-02	4.76E-09
Th-230	1.60E-02	5.50E-04	8.50E-11	1.31E-02	5.68E-01	8.78E-08
Th-232	3.10E-04	2.70E-03	4.20E-10	1.29E-02	5.32E-02	8.28E-09
U-234	1.70E-02	2.80E-04	4.30E-11	2.21E-02	5.19E-01	7.96E-08
U-238	1.70E-02	2.50E-04	3.90E-11	2.21E-02	4.63E-01	7.22E-08
U-235	8.60E-04	2.70E-04	4.20E-11	2.21E-02	2.53E-02	3.94E-09
				TOTAL	2.73E+00	4.22E-07

P5e

POPULATION - INGESTION OF FOODSTUFFS
GROWN ON REPEATEDLY FERTILIZED SOIL
for: 1 star Treat Sludge (Fertilizer)
G= 4.93E+06
S= 1.00E+00

PD(mr m) = (G * S * C * Uf * DFing)
PR(fat l cancers) = (G * S * C * Uf * RFing)

Nuclide	C		DFing	RFing	Uf	PD	PR
Po-210	4.00	-01	1.90E-03	2.90E-10	1.31E-02	4.91E+01	7.49E-06
Pb-210	4.00	-01	5.40E-03	8.40E-10	1.31E-02	1.39E+02	2.17E-05
Ra-226	6.40	-01	1.30E-03	2.00E-10	1.31E-02	5.37E+01	8.27E-06
Th-228	8.00	-03	4.00E-04	6.20E-11	1.29E-02	2.04E-01	3.15E-08
Ra-228	8.00	-01	1.40E-03	2.20E-10	1.29E-02	7.12E+01	1.12E-05
Th-230	8.00	-03	5.50E-04	8.50E-11	1.31E-02	2.84E-01	4.39E-08
Th-232	8.00	-03	2.70E-03	4.20E-10	1.29E-02	1.37E+00	2.14E-07
U-234	1.60	-01	2.80E-04	4.30E-11	2.21E-02	4.88E+00	7.50E-07
U-238	1.60	-01	2.50E-04	3.90E-11	2.21E-02	4.36E+00	6.80E-07
U-235	1.20	-03	2.70E-04	4.20E-11	2.21E-02	3.53E-02	5.49E-09
TOTAL						3.25E+02	5.04E-05